JOURNAL OF THE A·I·E·E·

SEPTEMBER 1926

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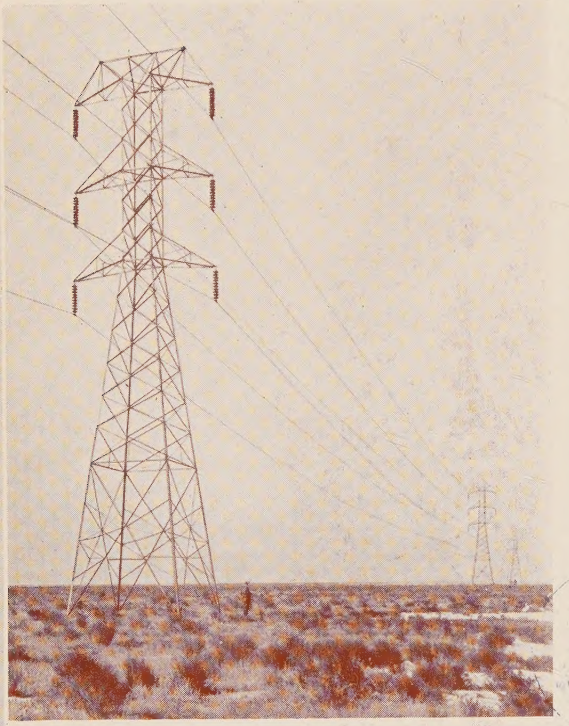
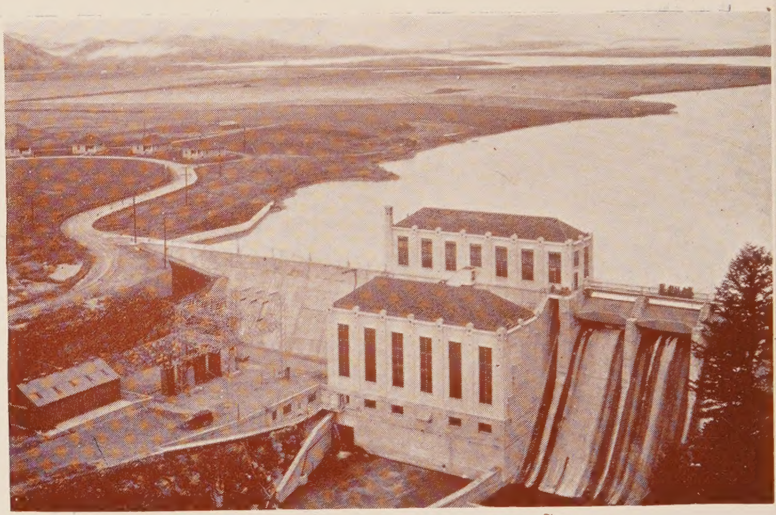
PACIFIC COAST CONVENTION NUMBER

BRYCE'S CANYON, SOUTHERN UTAH

SURFACE MINE-UTAH COPPER CO., BINGHAM CANYON, UTAH



130,000-VOLT TRANSMISSION LINE, UTAH LIGHT & POWER CO.



SODA HYDROELECTRIC GENERATING STATION

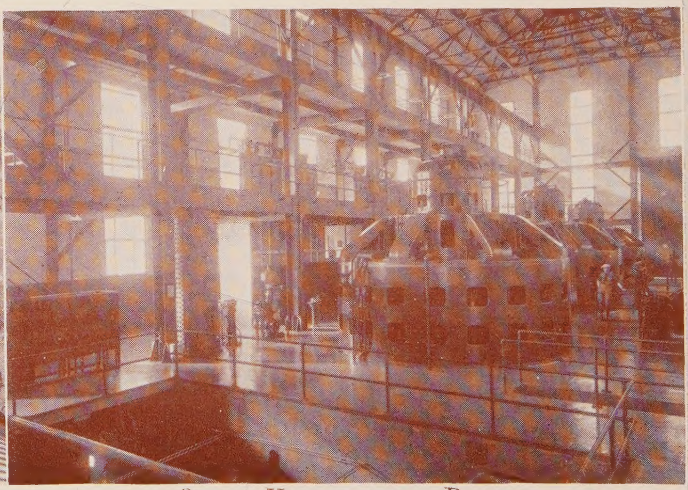
The A. I. E. E.

PACIFIC COAST CONVENTION

Salt Lake City, Utah

A few of the attractions offered by its location

GRACE HYDROELECTRIC GENERATING STATION, PIPE LINE 11 FT. IN DIAMETER 23,000 FT. LONG



ONEIDA HYDROELECTRIC PLANT, THREE 10,000-KW. UNITS

JOURNAL

OF THE

American Institute of Electrical Engineers

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Journal of the A. I. E. E.

Devoted to the advancement of the theory and practise of electrical engineering and the allied arts and sciences

Vol. XLV | September, 1926 | Number 9

Work of the A. I. E. E. Sections Committee

The Institute was founded in 1884. By 1900 it had attained a membership of 1142. In 1902-3, under the administration of President C. F. Scott, the establishment of Sections and Branches was approved and encouraged. Five years later, in 1907, there were 19 Sections and 17 Branches, with a total membership in the Institute of 4861. Together with the rapidly developing profession of electrical engineering and the impetus given by the activities of the Institute and its Sections and Branches, there has come the remarkable growth of the Institute during the last twenty years. This is indicated by the following tabulation:

Year	National Member-ship	No. of Sections	No. of Sections Meetings	Total Attendance at Sections Meetings	Amount of Sections Budget
1909	6,400	24	169	16,427	3,389.54
1913	7,654	29	244	22,825	12,645.18*
1917	8,710	32	265	31,299	10,596.96
1921	13,215	42	303	37,823	20,563.89
1924	15,438	47	381	58,945	25,219.31
1925	17,319	49	386	49,029	27,309.52
1926	18,158	51	405	58,959	30,060.76

The accelerated activities of the Sections and the Sections Committee were probably first clearly evident in connection with the work of the Sections Delegates Conference of 1921, conducted at Salt Lake City by the Sections Committee. Here it was evident that the Sections Delegates Conference was becoming an effective and important agency in the shaping of Institute policy through its recommendations to the Board of Directors. This is a natural result of the normal operation of such a body as defined by the Constitution and By-Laws and made up, as it is, of representatives from all the Sections distributed throughout the country.

That this is the case and the importance of the work done is shown by the following statement of some of the present policies now actively in force but which may be traced to initial action and recommendation of the Sections Committees and the Sections Delegates Conferences of the past few years.†

*Including an item of $4,345.29 for special and unusual expenditure.

†See printed report of Sections Delegates Conference, White Sulphur Springs, June 21, 1926.

1. Delegates' Conferences

1916 Program Committee to formulate program for annual conference and mail it to the Delegates in advance.

1922 Meetings to be held annually on the day before the Summer Convention proper begins.

2. Local Affiliations

1916 Subcommittee to report.

1918 Committee reported.

1919 Request for further study, resulting in the appointment of a special committee by the national societies.

1924 Statement of policy prepared and approved by the governing bodies of all four Founder Societies.

1925 Subject given further study and previous statement of policy approved.

1926 Recommendation to the Board of Directors for appointment of a special committee on contacts with the public for further study and report. Committee appointed.

3. Geographical Districts

1919 Division of the country into ten Districts and election of a Vice-President from each District.

1923 Traveling expenses to be authorized for the members of the Executive Committee of each District to one meeting each year.

4. Vice-Presidents

1923 Increase terms of Vice-Presidents from one to two years and provide that no Director shall hold office for more than six consecutive years.

1924 Traveling expenses authorized for one visit each year of each Vice-President to all Sections in his District.

5. Publications

1919 to 1923 Recommendations made which have resulted in the present well-defined policy regarding the Institute publications.

6. Transfers

1923 Plan recommended whereby desirable candidates for transfer to higher grades may be recommended to the Board of Examiners by other members.

7. Prizes

1923 First Paper and Best Paper Prizes for each District recommended. Now available.

1925 Recommended that a committee be appointed to prepare a statement of policy and procedure in connection with all national and regional prizes. Appointed and reported. 34 annual prizes now available.

8. Finances

1922 Recommended that the basis of financial support for Sections be changed from $100.00 flat plus $1.25 per member, to $175 flat per Section plus $1.00 per member. Now in force.

1922 Recommended that Sections be left free to expend their appropriations as they deemed best, but to send a report of expenditures to headquarters for the Finance Committee. Now in force.

9. Branches and Counselors

1925 Recommendation that a counselor be appointed for each Student Branch, these counselors in all cases to be members of the Institute and of the faculty in the institution in which their Branch is located.

1926 Recommended payment of travel expenses of counselors and Branch chairmen to Regional conventions and of District

Branch representatives to Sections Delegates Conferences. Approved by Directors. Referred to Finance Committee.

10. Speakers' Bureau

1922 Action taken to establish a speakers' bureau in limited form.

1926 Recommendation for appointment of a special committee to study question of public relations and development of more effective plan of speakers' bureau. Committee appointed.

11. Regional Meetings

1923 to 1926 Present policy of holding meetings under the auspices of the Geographical District officers developed. Regional meetings have been held as follows:

No. of Meeting	District	Location	Dates	Technical Papers	Attendance
1.	No. 1	Worcester, Mass.	June 5, 6, 1924	9	275
2	No. 2	Washington, D. C.	Jan. 23, 24, 1925	6	212
3	No. 1	Swampscott, Mass.	May 7, 8, 1925	21	370
4	No. 2	Cleveland, Ohio	March 18, 19, 1926	3	430
5	No. 5	Madison, Wis.	May 6, 7, 1926	9	180
6	No. 1	Niagara Falls, N.Y.	May 26, 27, 28, 1926	23	330

Plans are already under way for similar regional meetings of Section and Branch membership for the coming Institute year for Districts No. 1, 2, 3, 5, 8, 9, and it is expected that this list may be extended in the course of the year.

The accomplishments of recent years point the way to further advisable activites for the Institute membership in its effective Section and committee work for the future. The relations of the Section membership to neighboring membership of other technical and professional societies, to the Institute Student Branch membership, to its District and National Membership, to the general public and to itself are interesting and profitable fields for study. It is hoped that tangible and important results will come in the near future from the study in committees now being given to these relationships.

Harold B. Smith,
Chairman, Sections Committee.

Some Leaders of the A. I. E. E.

Comfort A. Adams, the 31st president of the Institute, 1918-1919, was born in Cleveland, Ohio, Nov. 1, 1868. His early education in the public schools of Cleveland was followed by four years at Case School of Applied Science from which he received the degree of B. S. in Electrical and Mechanical Engineering in 1890, the degree of E. E. in 1905 and in 1925 the honorary degree of Doctor of Engineering. During three years of his undergraduate period, Mr. Adams was assistant to Dr. A. A. Michelson in the Physical Laboratory.

After spending the summer of 1890 on a scientific expedition of explorations and surveys of the Muir Glacier district, Alaska, he served four months as engineer for the Brown Hoisting and Conveying Machine Co. of Cleveland and then joined the Engineering Staff of the Brush Electric Co. of Cleveland where under Sidney Short he took part in the design of the first geerless railway motor.

In September 1891, he accepted an appointment as Instructor in Electrical Engineering at Harvard University, was made Assistant Professor in 1895 and Professor of Electrical Engineering in 1905. Since 1914, he has been Lawrence Professor of Engineering.

When the Harvard Engineering School reorganized after the war, Prof. Adams was appointed Dean, but resigned shortly thereafter to accept the chairmanship of the Div. of Engineering National Research Council.

He has served in the capacity of consulting engineer for a large number of clients including Stone & Webster; American Tool and Machine Co.; The Okonite Co.; Edison Illuminating Company of Boston; Public Service Electric Company of N. J.; American Sugar Refining Co.; Warner Sugar Refining Co.; National Cable & Conduit Co., etc.

He has served the Institute as manager, vice-president and president; also as chairman of the Standards Committee; chairman of the Edison Medal Committee; chairman of the Committee on Code of Professional Conduct; and as member of several other committees, including the U. S. Committee of the International Electrotechnical Commission.

He has been very active also in the cooperation movement of the Engineering Societies, having organized the American Engineering Standards Comm. and being its first chairman. He reorganized the Engineering Division of the National Research Council after the war, serving as its chairman for two years. He was a member of the first American Engineering Council, took part in the organization of the Federated Am. Engineering Societies, has since continued on its Council and on the present Am. Engineering Council. He also served as member and president of the John Fritz Medal Board of Award.

He is author of several important papers in the general field of the theory and design of electrical machinery presented before the Institute during the past 20 years. His contributions to induction motor design were particularly significant.

During the world war he served as chairman of the General Engineering Committee of the Edison Commission of the Council of National Defense; chairman of the Welding Committee of the Emergency Fleet Corporation and chairman of the Electrical Engineering Section of the National Research Council.

Prof. Adams is a member of the A. S. C. E., A. S. M. E., S. A. E., A. S. T. M., N. E. L. A. and of the British Inst. of Elec. Engrs.; a fellow of the Am. Academy of Arts & Sciences, Am. Assoc. for the Advancement of Science and of the American Physical Society. He organized and was first president of the Am. Welding Society of which he is now an honorary member. He is also Director of the Am. Bureau of Welding.

Electrical Practise in the Lead-Silver Mines of Utah

BY LEONARD WILSON[1]

Non-member

Synopsis.—*Special features of industry react on selection of equipment. Speed of conducting operations directly affects value of property; the mining personnel has a somewhat unique psychology; the cost of providing space underground is enormous. Certain requirements result and equipment must be selected accordingly.*

Compressed air has been the only power medium and still reigns supreme for rock drills. Electric power has captured the field for large, underground pumps, hoists, and fans, but not for miscellaneous service. Mines have, and always will have, a complete distributing system for compressed air. In the future, they will also have distribution system for electric power.

Results of practical experience are outlined. Power cables should be of small capacity and all of the same size. Three separate types of protection should be used for overloads, short circuits, and grounds, respectively. Distribution is generally at 2300 volts but might, with advantage, be at 4000 volts, grounded neutral. Magnet switches have solved the problem of starting and controlling motors. Reduced voltage starting is undesirable. Sealed type bearings eliminate much bearing trouble. A new type of large hoist occupying the minimum of space is now being installed at the Park-Utah. The field of mechanical haulage is undeveloped, but conditions to be met are formulated. Mechanical loaders are beginning to receive serious attention.

* * * * *

THE lead-silver mining of Utah is a very important contributor of wealth to the State and presents several interesting and unique features as an industry using electric power, particularly in view of the fact that the use of power to replace manual labor and animal haulage is becoming of great importance in the reduction of cost of mining and the intensifying of production.

Any analytical study of present practise and the future trend of electrification must be based on a knowledge of the outstanding features of the industry, and in using the term *industry,* it is to be noted that this paper deals only with the operations of the large, established mining corporations.

The industry is essentially a combination of the processes of prospecting for new ore, extracting it, and marketing it. This calls for great skill in financing and in the broader functions of general management. The cost of borrowing money is high, the burden of taxation is beyond belief to those not acquainted with the facts, and the basic costs of labor and railroad rates are far above the average for other industries. These present handicaps may be viewed with optimism in the sense that there is great probability of their being decreased in the future, but they have a distinct bearing on the fundamentals of the mechanical operation of the properties.

Perhaps the most important result of these conditions is the necessity for speeding up the operations. The old idea that ore in the ground is the same as money in the bank no longer applies. The present value of a given probable tonnage is more than doubled if the rate of production is doubled. The human element—the psychology of the miners, bosses, and managers—also has a marked effect on the development of new mechanical methods.

Underground, conditions are fraught with physical hardship and danger hazards and the successful miners are of the hardy, adventurous, independent type, willing to go the limit and therefore rightly demand that all mechanical equipment shall endure the same hardships and hazards. There is also a feeling which may best be described as intense loyalty to all established and well-proved equipment, and this feeling of necessity carries with it an equally intense distrust of anything new.

One other feature of mining is of importance, and that is the enormous cost of providing space underground for the equipment and the much higher unit cost for larger excavations than for smaller ones. To meet the conditions above outlined, the electrical and mechanical equipment must be selected to comply with the following requirements:

1. Each and every part must be of sturdiest and most enduring design.

2. Maintenance and attention required must be reduced to a minimum.

3. The equipment must be compact and the dimensions of individual units must be suited to the sizes of shafts and tunnels through which they have to be transported.

4. Cost of installation must be minimized.

5. Equipment units must be standardized so that they may be moved from place to place and used under as wide a range of conditions as is practicable.

In the history of mining in this State, it is only a short time ago that all power used underground was transmitted by the mediums of compressed air or steam. Even at this time, there is no prospect of electric power supplanting compressed air for the operation of rock drills, and therefore there will always be a complete distributing system of compressed air available for the operation of small hoists, pumps, fans, conveyers, scrapers and loaders. For these items, the superiority of electric power is gradually proving itself and in due course of time, all the mines will have a complete distribution system of electric power.

For the larger underground power-using units, (pumps, hoists, and fans), electric power is a necessity. In the immediate future, there is going to be a rapid

1. Consulting Engineer, Salt Lake City, Utah.

To be presented at the Pacific Coast Convention of the A. I. E. E., at Salt Lake City, Utah, Sept. 6-9, 1926.

increase in the use of mechanical methods for underground handling of ore and waste. First, the equipment will be developed to use compressed air, but later on, it will be replaced by suitably designed electrical units.

The following is a review of present practise in the selection and use of electrical equipment for this industry.

Power is purchased at high voltage and transformed down to 2400 volts at outdoor substations of conventional design, with more liberal margins, however, on capacity and insulation. Such substations require no attendance during regular normal operation. The transmission of power from the 2400-volt bus bar to the points of use is by means of a number of small capacity cables, each feeding out through an oil circuit breaker with suitable time-limit overload protection. This development in the use of small capacity cables has in practise shown many advantages. In the earlier electrifications, cables as large as 250,000 cir. mils were used, but more recently, for the same amount of power, use has been made of three separate three-conductor cables of No. 4, B & S size. This particular size of conductor is well adapted as a standard for underground use, as its capacity is sufficient for the largest sized motor (300-h. p.) that is practicable underground, and its cost, installed, is less per unit of capacity than smaller or larger cables. With this subdivision of cables, it is permissible to use high grade rubber insulation without a lead sheath, but, of course, with a light metallic sheath for protective purposes. Such a cable has a low installation cost and a high salvage value.

The standardization of cable to a single size and type for all purposes is of great advantage to each individual mining property, in that it leads to great simplification in the protection of the cable system, and reduces the cost of the original installation and future changes and extensions. The effective space required for cables is less, in general, for a number of small cables than for one large cable.

With regard to protection of the cable system, separate methods are used for protection against overloads, short circuits and grounds. For overloads, the protective device is an oil circuit breaker with thermal type relays having thermal characteristics suited to the standard cable and therefore capable of carrying a very high overload current for a few seconds. For short-circuit protection, use is made of group circuit breakers with relays set for high current and short time interval. The grouping of the cables at a centralized underground switch is made to suit the particular conditions of the underground motor installations. For ground protection, a single ground-detector relay for each 2300-volt system operates an alarm, and the location of the defective insulation is determined by switching the various circuits. In a well installed system, such grounds are of rare occurrence, and if attended to at once, lead to no trouble whatever.

The voltage of motors is, in general, 2200 volts for 50-h. p. and larger sizes. It was the tendency in the past to shun such a high voltage—particularly for hoist motors—but now, with improvement in design of motors and the perfection of the magnet switch, the use of 2200-volt motors is preferable; in fact, if the manufacturing companies had not abandoned the old 4000-volt, grounded-neutral standard equipment at about the time that the mines were being electrified there would be many more mines in this district now using that voltage.

The selection of starting equipment is a matter of importance. Reduced-voltage starters are, in themselves, a source of trouble underground, and full-voltage starting is adopted wherever practicable. In all cases the starting should be by push button (unless it is automatic) in order to insure the switch being properly closed. For frequent operation, the hoist-type air-break contactor has proved superior to all others.

With regard to specific applications of motors for the surface plants, as well as underground, a few points are of interest.

For compressor drives, direct-connected, synchronous motors are standard practise and it is preferable to use automatic full-voltage starters with automatic air valves so that only one operation is necessary to put the compressor unit on the line. For surface hoists, the general practise is to use induction motors with full magnetic control. Ward Leonard control has many advantages, particularly in the matter of rapid and safe manipulation, but the additional cost is not always warranted. For underground hoists of large capacity, the limiting factor is cost of excavation for the hoisting equipment, head sheaves, and ropeways. An interesting solution of this problem has been worked out at the Park-Utah mine by the adoption of the Nordberg-Bollen design, in which a single head sheave functions as a hoist. In this installation, Ward Leonard control is used and the hoist, together with all the electrical equipment, is located in a rock chamber cut out above the top of the shaft. Complete remote control is used, with the operator on the level of the skip pocket.

For small and medium sized motors, the standard induction motor is about perfect if the bearings are properly maintained. The older designs of ring oiling bearings were not satisfactory, as they required too much attention and were liable to be robbed of oil for cleaning purposes. The newer types of sealed bearings and ball bearings are satisfactory.

The problem of underground haulage is far from a standardized solution. At present, the tendency is to use hand tramming or mule haulage whenever it is physically possible to handle the tonnage by those means. Practically no storage-battery locomotives are used, and trolley locomotives are used only when the weight of ore per train can be made as high as 30 tons. The standard gage is 18 in. and the standard

mine car, loaded, weighs about 3000 lb. A man can just tram a single car. A mule can pull seven or eight cars on the somewhat uneven grades of the smaller drifts. A four-ton trolley locomotive on the main transportation tunnels can handle about 30 cars. For complete electrification of the haulage, it is desirable to have two classes of locomotives, each operating, if so desired, as tandem units. The small size of 1½ tons would handle seven cars single, or 14 double, in the smaller drifts; and the four-ton size would handle 30 cars single, or, in a tandem unit, could handle 30 tunnel cars of about 2½ times the tonnage. It is to be noted that the cost of track facilities for handling trains is one of the big factors in the problem. It appears from some recent results that a double-trolley system is superior to storage batteries, and can be used where a single trolley is unsafe. It is important to note that with 1½-ton locomotives, it is not practicable to use the rail as a return for low-voltage operation because the surface cannot be kept clean enough.

In conclusion, it is to be observed that the methods in use are, of necessity, crude, but that the increasing use of electric power is having a very desired effect in demonstrating the advantage of more efficient operation and will lead to more complete electrification of all operations except rock drilling.

Iron and Steel Production

Annual Report of Committee on Applications to Iron and Steel Production*

F. B. CROSBY, Chairman

To the Board of Directors:

To anyone who has followed closely from its insignificant status at the beginning, on through the first and into the second quarter of this 20th century, the application of electricity in the iron and steel industry, the steady growth to its present gigantic proportions has always seemed inevitable, though none the less amazing.

In some respects, the year 1925-26 has seen all previous records broken in the rate of electrification. The applications of electric power have become so diversified that it renders entirely out of the question more than the briefest outline of outstanding features in the developments of the past year.

I. Generation of Power

The steam turbine continues to prove the most reliable of prime movers in the steel plant power station. With the increased economies in boiler room practise, with blast furnace gas as fuel, and the further use on the mills of cooling water from the condensers, the production cost per kw-hr. from the turbine driven generator, closely approaches that of the gas engine. Coal or oil can be used as auxiliary fuel supplementing the supply of blast furnace gas and thus avoiding delays which may arise due to shortage of gas during periods of castings or furnace repairs.

The thermal efficiency of the gas engine is very attractive and where an ample supply of blast furnace gas is available this prime mover finds warm support. Five new installations of gas-engine-driven blowers, and one gas-engine-driven generator are reported for the current year.

The ideal arrangement appears to be a combination of steam turbines, gas engines and purchased power, with dependence upon the gas engine and central station for the base load while the turbines float on the line carrying the peaks. Under these conditions a large block of power can be purchased at favorable rates owing to the comparatively low maximum demand charge, especially if hydropower happens to be available.

One steel company which is putting through a complete electrification program of old and new mills is building a modern power plant with two 12,500-kv-a., 6600-volt, 60-cycle, turbo generators to supply power for the plant. Steam will be obtained from blast furnace gas and powdered-coal-fired boilers designed for 300-lb. pressure at 180 deg. superheat.

There is no question but that blast furnace gas should be used as efficiently as possible and wherever possible, before any other fuel is considered. Considerable economies can yet be made in the use of gas for heating blast furnace stoves. This will leave more gas available for the generation of power, either through gas engines or boilers and turbines, for the production of steam for plant uses, or when mixed with coke-oven gas, for use in heating furnaces throughout the plant.

Coke-oven gas finds a ready application in practically every heating, reheating and annealing furnace operation in the plant, but where a large city offers a ready market, it is often necessary to restrict its use in the steel plant to effect an economic balance between city and plant consumption.

The steel industry is still looking to the central sta-

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F. B. Crosby, Chairman, Morgan Construction Co., 15 Belmont St., Worcester, Mass.

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W. C. Kennedy,	A. G. Place,	J. D. Wright.
	F. O. Schnure,	

Presented at the Annual Convention of the A. I. E. E., at White Sulphur Springs, June 21-25, 1926.

tions for an answer to the question of pulverized versus solid coal. In this field the opinion is prevalent that powdered fuel research and application are in the incubation stage and that developments in the near future may revolutionize present standards of boiler practise.

II. Distribution

Many steel plants have reached and passed the economic limit of 2200 volts for distribution. The large powers often required result in prohibitive current values at this voltage. This is reflected in excessive costs of protective oil switches and line losses even in the relatively short transmission distance from the load center to the numerous mill motors.

A distribution voltage of 6600 has become quite usual, so that only in the smaller plants, and in some cases where power is purchased, is 2200 volts standard. The increasing loads in the larger plants are taxing even the 6600-volt systems, but, so far, only one plant is reported as having main roll motors fed directly from a 13,200-volt system.

III. Main Roll Drive

Many of the mills laid out previous to the advent of the steel mill motor, now, each year, are reaching a point where, because of competition with recent equipment, it is necessary to throw them out or re-build them so far as possible along modern lines. The first consideration is usually the replacement of the original engine by a suitable motor and control.

One electrical manufacturer reports the sale of an aggregate of 33,270 h. p. of motors replacing engine drives during the past year. During this period the company has installed and placed in operation 31,000 h. p. (continuous rating) of reversing-mill motors and has taken orders for six additional reversing equipments aggregating 24,600 h. p. Three of these six units are replacing engine drives of existing mills, while two are for new mills which are to replace engine driven mills.

Notable among the reversing equipments installed during the year are two 7000-h.p. motors, the largest single armature machines thus far built for this service. An 8000-h. p. unit of slower speed but nearly 50 per cent larger in physical dimensions is, however, nearing completion in the factory.

Developments in the frequency converter type of alternating-current, adjustable speed drives provide for operation at constant torque above and below synchronism. This method of speed adjustment requires only two rotating machines,—the main motor and the frequency converter,—both on the same shaft. The slip energy of the induction motor is changed to line frequency in the frequency converter and returned to the line through speed adjusting transformers. Three units of this type, one of 770 h. p. and two of 1600 h. p. each, are now being built.

A 5000-h. p., 99-rev. per min., 60-cycle, induction motor built for a continuous billet mill drive is of interest particularly in that it is designed for 13,200-volt operation. Heretofore, except in one instance (see Report for 1925) main-roll motors have not been built for voltages above 6600 as it was thought that insulation troubles on higher potentials would be aggravated by the dirty atmosphere and conducting dust usually found in steel plants.

The necessity of maintaining constant speed relation between the several drives of modern tandem mills has brought about the development of a new method of control for compound wound, adjustable speed, direct current motors. This involves a series exciter and a variable potential field rheostat mechanically connected to the main shunt field rheostat, with resistance so proportioned that the series excitation is of the correct value to give very nearly zero speed regulation at any speed setting. This method of control is being applied to a 10-in., semi-continuous, merchant mill in three sections which are driven by 1000-, 1200- and 2000-h. p., d-c. motors respectively.

Another electrical manufacturer reports unprecedented activity in its steel mill business for the past year with an aggregate h. p. rating of mill motors sold from 1st June, 1925 to 1st May, 1926, of 102,910 h.p. This company also reports placing in operation a 4000-h. p. reversing drive in which the single motor is supplied from a fly-wheel motor generator consisting of two 750-volt generators permanently paralleled, a scheme first suggested by them in 1922 and now generally adopted.

This same electrical manufacturer also reports a new tonnage record for electrically-driven blooming mills made by a 40-in. mill, driven by one of its reverse equipments; namely 90,175 tons of ingots rolled in one month. A repeat order duplicating the electrical equipment was obtained for a 46-in. mill, using a motor rated 7000 h. p., 50 to 100 rev. per min.

Another of its installations of especial interest is a 9000-h. p. unity power factor, 107-rev. per min., 6600-volt, 25-cycle synchronous motor which, from the standpoint of continuous h. p. capacity, is the largest motor of any type used for industrial purposes in the United States or, so far as can be learned, in any other country. It is also notable in that it is the first really large synchronous motor to be used for driving a rolling mill. The motor may be started, stopped, or reversed from a master switch exactly the same as any other type of rolling mill motor. The Korndorfer system of control is used and the complete operation of starting on the low voltage tap of the auto-transformer, switching to a higher tap, applying field at the correct time, and throwing on the line, is taken care of automatically. In the design of the motor, particular attention has been given to obtaining very good starting torque characteristics. The excitation for the motor field is derived from a separate motor-driven exciter.

One of the best examples of motor drive for so-called tandem mills was put in operation about the first of the year. Practically every stand is driven by an individual direct-current motor, furnished with power from several synchronous motor-generator sets; a wide range of speeds is obtained by a combination of generator voltage and motor field control.

The aggregate capacity of the several motors driving this mill amounts to 15,850 h. p. (40 deg. cent.) The electrical apparatus is located in the best possible surroundings, emphasizing the growing importance which the mill operators are assigning to the electrical part of their equipment.

While the cost of such an elaborate drive is relatively high, the equipment is, on the whole, very economical; the flexibility and the wide speed range permits of rolling on this mill a great variety of products which would otherwise require at least two separate mills of a less flexible type.

The following tabulation includes only main mill motors on a continuous rated basis, in units above 300 h. p. as reported by the three principal electrical manufacturers in this country, up to 1st May, 1926.

	1923	1924	1925	1926
60-cycle	452840	478390	543440	586440
25-cycle	475825	490225	538450	582430
Direct-Current	299670	324860	430610	530060
	1228335	1293475	1512500	1698930

IV. Automatic Control

The year 1925 showed great activity in the application of automatic control to cranes and auxiliary mill machinery. Its dual functions of *control* and *protection* are now universally accepted so that there is now little opposition to its general use. Although there were no new developments of remarkable importance a most interesting feature was the rapidly increasing use of the inductive time element control system.

This system of control was commercially introduced in 1924 by one manufacturer and shortly afterwards a similar system was brought out by another. The essential features of these systems of control are: (1) the short circuiting of accelerating resistance within a definite time, regardless of the load, and (2) the securing of a time interval purely by electro magnetic means. In the first system, the time interval is secured by making use of the transient voltage induced in a transformer or "inductor" due to changes in the motor current. In the second system, use is made of the slowly decreasing magnetism of shunt-wound relays when their coils are short circuited. Both systems fill a long felt need. Theoretically, current-limiting control provides a valuable protection to the motor. Practically, the protection actually afforded in many instances is almost nil since the current-limiting relays must be adjusted to start the motor under the heaviest load which may be encountered. With current-limiting control, therefore, the motor starts slowly under heavy load and quickly under light load, in either case subjecting the motor to excessive current. On the other hand, time-element control imposes excessive current on the motor only when the motor has an excessive load to accelerate and thus gives the motor much better average protection.

Although the larger portion of these installations has been for the control of mill tables and other auxiliary drives, a very considerable number has been installed for the control of open-hearth charging machines, soaking-pit cranes and standard cranes, particularly for the bridge motions. Installations of particular interest include a dynamic lowering controller for a bucket hoist and an ore-bridge trolley controller. Recent installations placed in control rooms entirely separated from the mill proper with control panels mounted in continuous switchboards, resistors mounted overhead in tiers on structural supports, with foot walks between, and with ample provision for ventilation, mark the growing appreciation of the fact that proper and substantial installation contributes probably as much as first class equipment to continuity and economy of operation.

A very interesting development of the past year which will surely have an important effect on crane control is the increasing use of roller bearings. One large installation has been made of cranes equipped throughout with roller bearings even including the sheave bearings in the hook block. An obvious effect of these anti-friction bearings is to increase the free running speed of bridges and trolleys and the light hook hoisting speeds. This imposes a greater responsibility than ever before on the control equipment to protect the motors and gearing in plugging and emphasizes the necessity for reliable brakes and limit switches for the hoists. Brakes on the trolley motors, hitherto rather unusual, would appear to be necessary on a trolley equipped with roller bearings. In some cases the hoist control will need to provide some means of limiting the light hook hoisting speed.

Automatic control of the electro-pneumatic type is being applied to the control of two 275-h. p., compound-wound motors in parallel for the drive of a large bloom shear. The cycle for this machine requires a complete operation in about six seconds and the pneumatically operated contactors of the large capacities involved are much faster and more positive in action than magnetic contactors of similar capacity. The electro-pneumatic contactors are assembled in steel frame work, and make a more conpact and rugged controller than the usual contactors mounted on slate or other insulating panels.

V. Automatic Sub-Stations

The use of automatically controlled sub-stations in steel plants has increased very greatly since the first installation in 1924. An installation recently put into

operation provides for the automatic control of two 1500-kw. synchronous motor generator sets and of twelve 4000-ampere, d-c. feeders. This automatic equipment is in a substation with several large reversing mill drives with an attendant always present, but it was felt that the more reliable operation was of sufficient value to warrant the installation of automatic equipment just the same. Several other installations are being made for the automatic control of motor generator sets and a-c. and d-c. feeders.

VI. Yard Electrification

The Diesel electric locomotive of which special mention was made in this report last year has grown rapidly in favor as experience has demonstrated its possibilities. Larger sizes up to 60 tons or more are now available and with their proved economy and reliability appear to have successfully solved the dangerous problems of third rail or overhead trolley in the steel plant.

VII. Illumination of Yards and Buildings

This past year has seen a marked impetus in the increasing recognition of the value of good lighting in mill buildings and yard. More attention has been given to the specific requirements of different kinds of mills and to the different operations within a given mill.

The kw-hrs. required for lighting range from 10 to 15 per cent of the total power load and is an appreciable item in the total cost. More efficient lighting units have been developed of larger wattage yielding more light per unit current consumption and, incidentally, requiring less time for cleaning.

VIII. Electric Heating

The use of electricity for heating is increasing rapidly in a great variety of applications. One instance of especial interest is the heating of ingot hot tops.

Early in 1925 an equipment was installed for heating the tops for ingots,—primarily of monel metal and nickel. Before using this equipment, 3800 lb. of metal was poured to obtain a 3000-lb. ingot, the waste averaging 20 per cent to 30 per cent. Now 3250 lb. of metal is poured and 85 per cent of the ingots are used with very little cropping while a large percentage of the remaining 15 per cent is worked into commercial products.

The electrical equipment consists of one 1800-kv-a., three-phase transformer designed to supply power to the ingot heating equipment and also to serve as a spare for a six-ton arc melting furnace. Other equipment consists of one 10-per cent, three-phase, air core reactor for use in the 2200-volt circuit, instrument and control panel; also six automatic, single-phase, electrode regulating equipments for controlling the input to the arcs used to heat the top of the ingot.

IX. Electric Furnace

Last December, several units of the first commercial installation of Northrup induction furnaces operating at 480 cycles were put in operation. This particular installation was made for melting nickel silver and similar alloys, but these equipments have many possibilities in the heating and melting of ferrous metals and alloys, several applications being under consideration at present.

The initial installation consists of two motor-generator sets, each delivering 600-kw., single-phase, 1875 volts, 480 cycles, to six Northrup high-frequency furnaces, each generator being driven by a 3-phase, 60-cycle, 2300-volt synchronous motor, with direct connected exciter. To compensate for the low power factor and obtain best circuit conditions, a bank of capacitors is included with each furnace.

Last fall, the equipment for the first three-voltage-control arc melting furnaces was sold. These equipments are used with six-ton, three-electrode furnaces, one originally installed with a 1200-kv-a. bank of transformers and the two others with a 1500-kv-a. bank of transformers.

Each new equipment consists of a 2550-kv-a. bank of transformers which will deliver full output at 165, 156 or 147 volts and a lower capacity at 138, 120, 95, 85, 80 or 70 volts. Air core reactors of 25 per cent capacity for connection in the 11,500-volt circuit, together with suitable switching equipment, were also included.

The melter has a choice of several voltages to start the heating, probably using 2550 kv-a. at 165 or 156 volts, 2400 kv-a. at 138 for the intermediate voltage and a still lower kv-a. at the refining voltage,—probably 85 or 90 volts, depending upon the furnace equipments.

Marked economies are effected in furnace operation, especially from the standpoint of the life of the side walls and roof, together with possible reduction in electrode consumption.

In conclusion, I wish to give full credit to the members of this committee for their effort as individuals in gathering the data which forms this report.

MESSAGES FOR MISSOURI

A short-wave set, operating on four to eight meters, is aboard. It is to be used to send out messages that can be picked up by amateurs in case of necessity at great distances. Some operator in Missouri or deep in the interior of Europe may hear this set during the Fonck flight and relay the message by wire to his government if the call is an S. O. S.

Both these sets are operated on storage batteries that are charged by two tiny generators. Each generator is driven by a fan with four-inch blades extending out into the "air slip" or stream of air that passes the plane during flight.—*Elec. Rev.*, July 25.

Engineering Education—Its History and Prospects

BY HENRY H. HENLINE*
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Synopsis.—A brief history of the development of engineering education in the United States and a consideration of the usual type of curriculum in particular branches of engineering are followed by reasons for the development of a new type of curriculum and a discussion of its principal characteristics.

The recently adopted curriculum leading to the degree of Bachelor of Arts in Engineering at Stanford University is given in detail. The ideals discussed in the paper are emphasized by a few selected quotations from statements of leading executives and teachers.

IN order to gain a true perspective of the subject of engineering education, one must consider its early history in the United States. The first American colonies were forced by Parliament to limit their production to agriculture and raw materials, and when they made the non-importation agreement in 1774, there appeared an urgent need for skilled workers in all mechanic arts. This situation was relieved by the formation of societies which exerted all possible effort to encourage the useful arts and by prizes offered "for the best achievement in every essential line of industry." After the war, similar activities were made necessary by the fact that England attempted to stop the development of industries by underselling methods.

During the years immediately following the war, many engineering developments were made, notably:

1787 —First flour mill machinery.
1790 —First textile mill driven by water power
1793 —Invention of the cotton gin
1801 —First high-pressure steam engine
1801 —High-capacity double steam pump
1807 —First steamboat
1786-93—Several canals begun

The war of 1812 again made it necessary that American industries manufacture all necessities, and this, together with the fact that much of the soil was becoming exhausted, produced a very urgent demand for scientific information which would lead to greater production in both agriculture and manufacturing.

As a result of this demand, the Rensselaer Polytechnic Institute was established at Troy, New York, in 1824. The curriculum, which was one year in length, contained a great variety of subjects. During the last nine weeks of the year, a study was made of the practical applications of the sciences previously studied. In 1835, instruction in civil engineering was added and students who completed the new curriculum were awarded the degree of Civil Engineer. Following a thorough study of instruction in French technical schools, the Rensselaer curriculum was lengthened in 1849, to three years. The first half of the curriculum was planned so as to lay a general foundation for all engineering, and the last half contained courses designed to allow for specialization in some particular branch.

In much of the early demand for such schools, the need for training as an aid to industrial production was very strongly emphasized, but there was also a rather insistent demand for instruction in science as part of a liberal education.

The Lawrence Scientific School at Harvard and the Sheffield Scientific School at Yale were established in 1847. At the same time, the University of Michigan decided to give a course in civil engineering. No other engineering schools were established before the Civil War[1].

One of the most significant steps ever taken in providing for higher education was the passage by Congress of the Morrill Act in 1862. By this Act, the National Government presented to each State in the Union 30,000 acres of public land for each senator and representative in Congress. The purposes as stated in the Act were, " . . . the endowment, support, and maintenance of at least one college, whose leading object shall be, without excluding other scientific and classical studies, and including military tactics, to teach such branches of learning as are related to agriculture and the mechanical arts, . . . in order to promote the liberal and practical education of the industrial classes in the several pursuits and professions of life."[2]

The results of this Act were extremely gratifying to those who had been appealing for more technical schools. In 1870 there were seventeen such schools as compared with the four established before 1862. The number continued to increase very rapidly, and there were forty-one in 1871, seventy in 1872, and eighty-five in 1880[1]. At the present time there are approximately 130 engineering schools of college grade in the United States.

A number of these early schools were called industrial universities because the greatest demands for them had been based on industrial needs. The idea that manual labor occupied an important place in their training soon became so widespread that many objections to

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1. For references see end of paper.

such names arose, and changes were made. For instance, the Illinois Industrial University became the University of Illinois in 1885.[3]

Although the first schools offered civil engineering only, the curricula were soon extended to include several branches of science and engineering. The Massachusetts Institute of Technology, which was established in 1865, offered six four-year curricula as follows:

Civil Engineering
Mechanical Engineering
Mining Engineering
Practical Chemistry
Architecture
General Science

The first curricula of the Illinois Industrial University, established in 1867, were:[4]

Agriculture
Polytechnic—including
 Mechanical Science and Art
 Civil Engineering
 Mining and Metallurgy
 Architecture and Fine Arts
Military
Chemistry
Natural Science

Four years were required for the completion of each. The above examples are fairly representative of curricula offered by all of the early technical schools. The general plan in all cases was to provide training in mathematics, drawing, physics, chemistry, etc., in the earlier parts of the curricula, and to have the work in applied science follow such training according to the plan used in French schools. English and foreign languages were usually included in the curricula.

The number of curricula in engineering increased very rapidly with the extensive development which occurred in the applications of engineering knowledge of all kinds. There are now available curricula in about forty branches of engineering, including aeronautical, agricultural, architectural, automotive, ceramic, chemical, civil, electrical, marine, mechanical, metallurgical, mining, sanitary, etc.

The great increase in the number of curricula offered has been accompanied by numerous changes in their content. The chief tendency has been to include more technical subjects to keep pace with the phenomenal expansion of engineering activities. This expansion itself has made even more necessary than before a very thorough education in the fundamental subjects. Hence, serious overcrowding has resulted.

This has been relieved to some extent in many schools by the growth, from each curriculum in a particular branch of engineering, of several curricula covering the various sub-specialties. This process is only a partial remedy, however, because some of the sub-specialties have grown into branches of great magnitude, and the growth has by no means ended.

The type of curriculum now in most general use is one leading to a Bachelor's Degree in a particular branch of engineering (any one of approximately forty) at the end of four years. Such a curriculum contains a common core of subjects required of all engineering students, and consisting of the following groups of subjects:[5]

Science: Mathematics, chemistry, physics, mechanics
Mechanics Arts: Drawing and shop work
Humanities: English, foreign language, economics, etc.

These foundation courses are followed by the various engineering subjects considered essential in the specialized curricula. As a general average, the student's time during the four years is distributed about as follows[6]:

Languages and humanities...........19 per cent
Mathematics and sciences............29 per cent
Engineering subjects.................52 per cent

Since the languages and humanities group receives only 20 per cent of the time, and English and foreign languages are usually strongly emphasized, little or no time is spent on certain very important subjects such as biology, economics, geology, history, political science, psychology, business law, etc.

The group of subjects including mathematics and the sciences, principally chemistry and physics, receives strong emphasis in nearly all curricula because these subjects really constitute the foundation of all engineering. These, together with the group mentioned above, are usually given in the first two years.

Drawing and shop work are usually considered very essential subjects, and receive their proper proportion of time. The value of shop work, however, has been seriously questioned during the past few years. Many experiments in the handling of such courses have been tried. In a few schools, the university shops have been operated on a production basis in order that students might have experience as production managers, foremen, machine operators, etc., and thus receive a training designed to enable them to understand shop operations of all kinds. Others have developed cooperative courses with neighboring industries so that shop training as well as many other kinds of training can be obtained under practical industrial conditions. Throughout the period covered by these experiments there has been a considerable strength of opinion that shop work is being allowed to take time which should be allotted to other subjects, and the reasons why all engineering students should develop facility in handling tools have not been clearly shown.

Following these two years of preparation, the latter half of the curriculum is usually nearly filled with engineering subjects. This makes it necessary that each student decide early in his university career which one of the many branches of engineering he is most interested in and best fitted for. The time at which such a decision must be made if he is to graduate with his class depends upon the school chosen. In

some it is as early as the beginning of the first year. A large number require this decision at the beginning of the second year, and about one-fourth permit it to be made as late as the beginning of the third year. Very few schools permit greater delay[7].

During the work of the last two years, there is usually a considerable number of courses dealing with the various phases of the specialty chosen. There are also courses in related branches of engineering. Thus a student in civil engineering is usually required to take a course or two in electrical and mechanical engineering, and a student in electrical or mechanical engineering usually takes surveying in the civil engineering department. However, the major portion of the time is spent on the subjects closely related to that chosen for specialization.

In connection with the very thorough investigation of engineering education now being conducted by the Society for the Promotion of Engineering Education, many questionnaires have been used to secure information on all phases of education and related matters. One such questionnaire now being circulated gives ten divisions of electrical engineering, and asks which ones are considered so important that special curricula in them should be offered.

A serious result of the tendency to keep adding technical courses to curricula which are already completely filled is found in many schools in which the requirements for graduation in engineering include a considerable number of units more than required for graduation in other curricula. It is quite common to find this situation made more serious by the fact that there are few if any courses in subjects which prepare men for dealing with people, namely, citizenship, economics, political science, etc., or subjects which provide any cultural value. Many such curricula are extremely rigid, and allow almost no choice of subjects. Therefore, students are expected to follow a certain list of courses with very little thought as to their own interests.

The established order of subjects in most curricula, *i. e.*, languages, chemistry, physics, mathematics, mechanics, drawing, and shop work in the first two years, and engineering subjects in the last two, is often severely criticized because practical applications always follow theoretical principles. Another result of this order of subjects is that the students have very little contact with engineering or engineering faculty members during the first two years. Several institutions have tried the experiment of giving engineering problems throughout the first year. The success has apparently been great, as such work stimulates the students' interest and assists in making the final decision as to the special branch of engineering in which they wish to specialize. However, it seems to be impossible to coordinate theory and practise in a curriculum in such a manner as to meet all objections. Certain fundamental subjects must precede the more advanced subjects, and no Utopian scheme which includes all subjects mixed in proper proportions and arranged in ideal order has been proposed. It seems that the students of a worth while type should be able to maintain their interest through two years of work in fundamental subjects. It is a serious question whether one who cannot do so does not more properly belong in a trade school than in a university.

The investigation now being conducted has shown that about 62 per cent of the students admitted to engineering curricula fail to graduate, and the elimination occurs largely in the first two years[8]. This fact is causing a serious consideration of the factors involved with the hope that the mortality can be reduced. It has been suggested that the adoption of two-year curricula leading to a certificate or diploma, and preparing students definitely for certain kinds of technical employment, might be a satisfactory solution. There are a number of very serious objections to this procedure. Such a two-year curriculum would not provide the most suitable first two years' training for those who wish to complete a four-year curriculum, and it would be difficult or impossible for most institutions to provide facilities and personnel to handle both classes of students. The most serious objection, however, is the fact that this would definitely lead many able men into mediocre technical positions where their future progress would be slow. The failure of a student in mathematics or some of the other subjects placed early in the engineering curricula does perhaps indicate that he cannot be successful in the higher types of technical work, but it by no means indicates that he cannot become a successful man in the business or management side of engineering.

It seems obvious that the greatest need is for some means of determining what each student is best fitted for and the type of intellectual effort in which he is most interested. If each could receive expert assistance in the determination of his strongest natural aptitudes, the number of such eliminations would be greatly reduced. Many men now turned out as failures in the engineering curricula would be highly successful in some field of human endeavor, and this would be a far more satisfactory outcome than would be obtained by guiding all such men into mediocre technical positions.

To sum up the characteristics of most of the curricula now in effect: They are too rigid in that little allowance is made for the interests or initiative of the students when a decision has been made to specialize in a particular branch. This decision must, in most cases, be made before students are mature enough or have had sufficient experience to decide wisely. They devote too small an amount of time to broad education and too much to narrow specialized training.

A number of universities have developed five- or six-year curricula in order that more general subjects might be included without omitting the engineering courses which are considered necessary. In several

cases no degree is received until the completion of the entire five- or six-year period.

The cooperative type of education has some well recognized advantages in schools of all grades. The Massachusetts Institute of Technology and the University of Cincinnati are the two outstanding examples in the engineering field. At the former, the cooperative curriculum is five years in length. The first two years are the same as the usual electrical engineering curriculum, but during the last three years, alternate terms, including summer terms, are spent in the industries. The fifth year is devoted to graduate work and research in both the Institute and the companies. Each man has a choice of manufacturing and utility companies, but works in the same company during the three years. His compensation averages about $1500 for this period.[9]

The ideas expressed below, regarding some of the ideals of engineering education, are not those of any one man alone, but represent the aggregate opinion of the author and others. An earnest effort has been made to include the best thought on the subject.

The requirements of engineering education could be determined more definitely if there were a generally accepted definition of engineering. The following definition was given in his president's address in 1908, by Past-President Stott:

> "Engineering—The art of organizing and directing men, and of controlling the forces and materials of nature for the benefit of the human race."[10]

The first part of this definition shows that an important part of education consists of subjects which will enable those men who will become executives to develop more rapidly.

Probably a large majority of undergraduates in engineering schools believe they will be engaged for many years in work primarily technical. The results of the S. P. E. E. investigation show that of the three most recent classes 71 per cent are in work primarily technical, while more than 70 per cent of those in classes out fifteen years or more are in work primarily administrative.[8] Such records certainly indicate clearly that a broad education is more important than training in technical subjects. In 1916 a circular letter was sent to thirty thousand members of the four large engineering societies requesting them to number six groups of qualities headed Character, Judgment, Efficiency, Understanding of Men, Knowledge, and Technique, in the order of importance given them in accounting for engineering success and in considering young men for employment. Of the seven thousand replies received, 94.5 per cent placed the Character group at the top of the list, and about the same number placed Technique at the bottom[11]. Success in engineering obviously depends upon many factors besides technical knowledge and skill. The really successful engineer must be able to coordinate theory, practise, and economics, and to handle men. As shown above, most of the engineering curricula now in effect were planned in the earlier years of engineering education, and the changes made since have consisted principally in the addition of more technical courses. Most of the curricula furnish excellent preparation for certain types of work into which some of the graduates enter. On account of the extremely rapid progress that has been made in many branches of engineering during the past few years, the applications of engineering knowledge are now so many and so diversified in character that any curriculum designed to meet directly certain needs in industry may indeed prepare men in a most excellent manner for those needs, but fail utterly to prepare them for a great range of engineering problems, both executive and technical, which all graduates will be called upon to solve.

The very strong and growing tendency to choose executives from men with engineering training is a force which must be reckoned with. Problems which executives meet are becoming so complex and so closely associated with fundamentals of engineering that some technical knowledge is essential. No one believes the schools can train executives, as ability in this direction depends primarily upon inherent characteristics. However, if engineering graduates are to receive their fair share of such positions, they must be given the broad, general foundation which is absolutely essential.

During the past few years many high executives in some of our largest industries have advocated a broad type of training for engineers. In employing recent graduates, they prefer to obtain men who have had a thorough training in fundamentals and who have not specialized in some small branch of one of the principal types of engineering.

What, then, are the principal characteristics of a satisfactory engineering curriculum? The answer to this question depends upon the types of activity for which the schools attempt to prepare men. In the present stage of development, it seems necessary to recognize the needs of two general groups of students, *viz.*, those who expect to spend their lives in highly technical design or research, and those who will be engaged in commercial, industrial, or administrative phases of engineering. Both groups need a broad foundation consisting of such subjects as English, economics, biology, geology, history, business law, political science, etc., and thorough training in chemistry, physics, mathematics, mechanics, and other subjects which make up the heart of engineering. Such training should be mixed with and followed by courses giving the fundamentals of all of the principal branches of engineering, and there should be a reasonable amount of time available for elective subjects. Thus far there is no serious difference between the wishes of executives in industry and teachers of engineering. It therefore seems that the chief cause of argument is the relatively small group of men who will engage in research and other highly technical phases of engineering. This group must have better oppor-

tunities for the development of research ability and for specialized study than can be provided in any four-year curriculum which contains sufficient training in fundamentals. It seems clear that the usual type of four-year curriculum fails to meet the needs of all except those who wish to remain in the specialized divisions of engineering which do not require either a very broad training or an advanced technical education.

Many professional engineers believe a university curriculum should provide broad and thorough training in the fundamentals of engineering, and that considerable emphasis should be placed upon humanistic subjects such as English, economics, sociology, history, etc., not merely on account of their usefulness to the engineer, but also on account of their broadening influence[12]. Another phase of the investigation of engineering education now being conducted has developed the strength of this demand. The opinions of 1931 graduates of the classes of 1919, 1914, 1909, 1904, 1899, 1894, 1889, and 1884 on the principal objectives of engineering education are as follows[13]:

	No.	Per cent
To train broadly for the general needs of the industry	398	20.6
To train for specific needs of specialized divisions of engineering practise	229	11.9
To provide the former type of training for the majority, but provide the latter type for those who desire to spend the additional time required	1304	67.5

The enormous physical plant which has been built up during the last few decades has produced problems never thought of in the early engineering curricula. The country-wide net-words of railroad, telephone, power, and radio systems have brought with them a host of problems in all branches of engineering, ranging by degrees from management, with all of its extremely complicated personnel and technical questions, on the one side to the most advanced scientific research, with its exacting demands in mathematics and the sciences, on the other. The size of the field in which a young engineer finds himself shows clearly the futility of any four-year curriculum of a specialized nature. The only adequate preparedness for such a field is a broad education in the humanities, fundamental sciences, and engineering fundamentals.

The results of the investigation indicate that the most serious criticism of engineering education arises from the lack of training in business and economics[14]. The fact that success depends largely upon a good understanding of those subjects seems to be very generally recognized.

It has been said that engineering graduates of the past have risen to high executive positions and that this indicates that no great changes in curricula are necessary. Many of the questionnaires covering various phases of the investigation contain replies which show that in general engineering alumni think the curricula were not seriously deficient in any important respects except in the lack of business and economics. It must be remembered, however, that the questionnaires were planned to bring out the facts regarding existing curricula, and those who answered them were given no real opportunity to express their opinions of the recent movement toward more liberal engineering curricula.

In 1920 Stanford University put into effect the Lower Division plan which replaces the major department system during the first two years. The principal object is to require more training in fundamental subjects. During this period, the students are registered under the supervision of the Lower Division Committee which is appointed by the President. Each is required to take certain subjects and to choose other subjects from specified groups. Some of the requirements can be met by certain high school subjects. The requirements do not completely fill the first two years, and the remainder of the time can be devoted to electives. The following is a brief summary of the requirements[15]:

Group Requirements

I	Languages and literature and formative art	18 units
II	Natural sciences and mathematics	18 "
III	Social sciences	18 "

Subject Requirements

English composition	6 "
Foreign language	22 units in one, or 15 units in each of two foreign languages
May be anticipated in high school in whole or in part.	
Biological science	9 units
Physics or chemistry	9 "
One of the sciences may be anticipated in the high school.	
American history	9 units
General history	9 "
One of the history requirements may be anticipated in the high school.	
Citizenship	12 units

At the beginning of any quarter, a Lower Division student may designate the department in which he expects to register during the last two years. Those who thus make a tentative choice of major subject are then advised to consult the department regarding the most suitable courses to take as electives during the first two years.

In the autumn of 1924, the President appointed a special committee made up of representatives of all of the engineering departments, and requested that the various phases of work in engineering be considered and recommendations be made to him. That committee presented its report in March 1925. In this it recommended that a School of Engineering be organized, that a more general type of engineering curriculum leading to the degree of A. B. in Engineering be adopted, that the department curricula, with certain modifications, be retained at the option of the departments, and that two-year graduate curricula leading to the degree of Engineer be adopted by those departments

which had been requiring only one year. The recommendations were adopted by the University, and Professor Theodore J. Hoover, Executive Head of the Department of Mining and Metallurgy, was appointed Dean. Committees were appointed last October, and the registration of students in the tentative form of general engineering curriculum was begun in January 1926.

A revised form of curriculum has recently been adopted by the Faculty of the School of Engineering, and a copy of it is given below.

FOUR-YEAR CURRICULUM LEADING TO THE DEGREE OF BACHELOR OF ARTS IN ENGINEERING**

FIRST YEAR, TOTAL UNITS, 44

Subject	Course No.	Autumn	Winter	Spring
Foreign Language		3	3	3
Linear Drawing and Lettering	C. E. 1, 2	..	1	1
Chemistry		4	4	4
Co-ordinate Geometry	Math. 10, 11	3	3	..
Calculus	Math. 21	..	..	3
Citizenship	Citizenship 1-3	4	4	4
Total		14	15	15

SECOND YEAR, TOTAL UNITS, 46

Subject	Course No.	Autumn	Winter	Spring
English Composition	Engl. 2a, 2b	3	..	3
Freehand Drawing	M. E. 11	3	..	..
Calculus	Math. 22, 23	3	3	..
Heat and Electricity	Physics 13, 14	..	4	4
Mechanic Arts	M. E. 1, 2 or 3	*..	2	2
Descriptive Geometry	M. E. 10	..	4	..
History		3	3	3
Extemporaneous Speaking	Engl. 7	3	..	..
Elementary Machine Drawing	M. E. 12	..	..	3
Total		15	16	15

THIRD YEAR, TOTAL UNITS, 45

Subject	Course No.	Autumn	Winter	Spring
Theoretical Mechanics	C. E. 30, 31	5	5	..
Hydraulics	C. E. 106	..	..	5
Surveying	C. E. 20	5	..	..
Engineering Geology	Geol. 1a	5	..	..
Electricity in Engineering	E. E. 102, 103	..	3	3
Elementary Accounting	Econ. 3	..	5	..
Principles of Mining	M. & M. 101	..	..	5
Electives		..	2	2
Total		15	15	15

FOURTH YEAR, TOTAL UNITS, 45

Subject	Course No.	Autumn	Winter	Spring
Mechanics of Materials	C. E. 110	5	..	..
Pyrometallurgy of Iron and Steel	M. & M. 105	..	3	..
Exposition	Engl. 131	4	..	..
Business Law	Law 100	4	..	..
{ Prime Movers	M. E. 123		5 or	.. }
or Elementary Machine Design	M. E. 113	..	4	.. }
Engineering Economics	C. E. 130	..	..	3
Human Relations in Business		..	3	3
Electives		2	4 or 5	9
Total		15	15	15

*All these Mechanic Arts Courses are given in the Autumn, Winter, and Spring Quarters. Any two courses may be chosen by the student, limited only by the capacity of the laboratories. Although scheduled for the Winter and Spring Quarters, sufficient registration is desired for the Autumn Quarter to make operation of all three laboratories possible.

**Since the presentation of this paper before the San Francisco Section, minor corrections have been made in this schedule to place it in complete accord with the curriculum appearing in the Stanford University Announcement of Courses for 1926-27.

This curriculum is founded on the belief of many that any considerable amount of specialization in engineering subjects during a four-year course is undesirable. All students should have a good foundation in general or cultural subjects. In addition to this, engineering students must have rather extensive training in chemistry, physics, and mathematics. There is a number of subjects such as mechanics, hydraulics, surveying, geology, business law, etc., which all engineering students should take. Finally, a young man who hopes to become a broad minded and well balanced engineer must have some knowledge of the contents of all of the principal branches of engineering, first, in order that he may be able to choose more intelligently the branch he wishes to follow as a specialty, and, second, in order that he may be able to consider all problems in their proper relation to the whole field of engineering. It is desirable also that such a curriculum allow a reasonable amount of time for elective subjects.

The above curriculum is not considered final. It is hoped that improvements can often be made in it. However, we believe it does follow closely the ideals expressed above.

The decision has recently been reached that the A. B. degree will not be awarded in the separate branches of engineering at Stanford after 1929.

The graduate study in each department is to continue over a two-year period leading to the degree of Engineer in the various branches. It is firmly believed that students who complete the six years will be very much better prepared for their life work than are those who take a more specialized course for four years and then one year of graduate work.

The question will often arise as to whether students who complete the four-year curriculum only will be prepared to begin work in certain engineering organizations. It is true that they will not be as well prepared in a certain few special phases of engineering as would the graduates of a more specialized curriculum. However, they will have a much wider range of choice, and need not feel limited to only a few specialties. If they devote their electives to carefully chosen courses, there need be no feeling that they are not prepared to become immediately useful. Future progress should be materially faster due to the broad foundation.

A few quotations from statements of leading executives and engineers will emphasize some of the statements made above.

SECRETARY OF COMMERCE HERBERT C. HOOVER[16]

"There is somewhere to be found a plan of individualism and associational activities that will preserve the initiative, the inventiveness, the individual, the character of man and yet will enable us to socially and economically synchronize this gigantic machine that we have built out of applied sciences. Now, there is no one who could make a better contribution to this than the engineer, but to make that contribution our engineers in the future have got to have a broader and stronger place in our world affairs than they have today. We cannot be turning men out of our universities as we are in many cases today purely mechan-

ical machines devoted to some theory built on applied sciences. If the engineer is going to take his part in this community, is going to give expression to those things that he can express best, he must start with a sense of his public obligations as well as his professional knowledge."

* * * * * *

* * * "but we had better reduce the volume of science and applied science we are pouring into our young men in order to make room for some stimulation of their public relationships, some realization of their public obligations."

F. C. PRATT, VICE-PRES., GENERAL ELECTRIC CO.[17]

"Voicing my own opinion on this subject, we are not looking to the colleges and technical schools to turn out finished engineers, but we do look to them for a steadily increasing supply of young men who have been thoroughly trained in the fundamental theories of the mathematical and physical sciences, and to the fullest practicable extent in economics and in what are commonly called cultural studies. We believe that, with this ground-work thoroughly prepared, the large industries are in a particularly favorable position to offer exceptional opportunities to young men for gaining practical knowledge and experience along special lines.

"In this connection, I wish to make it quite clear that in the foregoing remarks I am not including those exceptional students who by natural qualifications and inclinations are prepared to pursue post graduate studies in theoretical work in any branch of science or engineering which contributes to the industry."

F. C. PRATT[18]

"My observations also leads me to the conclusion that the percentage of those who fail to attain a reasonable degree of success is greater in the group of men of mediocre ability but narrowly specialized education than in almost any other group coming within my knowledge."

PROFESSOR EDWARD BENNETT, UNIVERSITY OF WISCONSIN[19]

"One of the most gratifying developments of recent years has been the recognition on the part of the engineering industries that they do not wish to have the engineering colleges train men for immediate service in their specific fields."

DEAN F. L. BISHOP, UNIVERSITY OF PITTSBURGH[20]

"There are two factors which enter fundamentally into the life of an engineering student. One is education, the other is training. In the very early days of the engineering school, education was the controlling idea; later, training or specialization became the controlling factor. In other words, we shaped our courses, modified our curriculum, and selected our teachers with the sole purpose of graduating professionally trained engineers.

"The reaction soon became evident. The cry went up that the engineer, although thoroughly trained, was narrowly educated. He lacked the proper perspective of life. He was unable to grasp the economic principles underlying great problems. He was too intent upon design and the solution of specific problems.

* * * * * *

"We must look forward to the time when engineering schools will consider themselves as educating a large body of men who will become effective managers of the industries and who will exert, through their education and training, an important influence on the political and social side of the community.

"If our engineering schools will look upon the education and the training of this large mass of men as their primary object, and delay the specialization and technical training to additional years in the schools or industries, our instruction will be changed to meet this demand so that the emphasis will be placed more on education and less on specilization. Our teachers will not be such highly specialized technical experts but that they will be broadminded educators. The public will show an increasing confidence in our graduates because they will be educated as well as trained."

DR. F. B. JEWETT, VICE-PRES., AMERICAN TELEPHONE AND TELEGRAPH COMPANY[21]

"Consequently I am interested in having those young men who come to us and who are going to be the leaders of our business of the future well grounded in the sciences. First, because we need them in the technical side of our business, and second, because I believe we are going to need them in a larger measure as the recruiting source for the executive directors of our business in years to come."

JOHN MILLS, DIRECTOR OF PUBLICATION, BELL TELEPHONE LABORATORIES, INC.[22]

"After we have answered these intermediate questions, we shall probably agree that we turn to the colleges in the hope of obtaining men of good mental ability and personality, who have acquired habits of thought and study which will enable them to see broadly the business and technical problems of the future, to analyze the factors involved, to arrive objectively and without prejudice at solutions, and, through personality and executive ability give to those solutions weight and effectiveness. We look, I believe, for trained brains in vigorous bodies with pleasant but dynamic personalities; men who may make creative contributions to our respective businesses or arts and, in a sufficient number of cases, develop as capable executives."

DR. M. I. PUPIN, PRESIDENT, A. I. E. E.[23]

"Nothing resists a change so obstinately as the mental attitude of man. The history of science from Archimedes to Newton offers many illustrations of this well-known fact. The change in the mental attitude of our age is one of the greatest achievements of our intellectual renaissance. Less than two generations ago, educational training was expected by many to operate like a penny-in-the-slot machine; that is, learn your lesson and convert your learning into cash without much delay. The so-called practical man who managed our American industries was at that time an ardent advocate of this utilitarian theory. He worshipped the art of making a living. Franklin and Lincoln, my patron saints, had no sympathy with this theory. The art of making a living was not the determining factor in their schooling, but the art of making life worth living was everything to them. They would find no fault with the American college because its diploma does not testify that college graduates are loaded with a knowledge of the art of making a living, provided, however, that they carry with them some definite ideas about the art of making life worth living, not only their own individual life, but also the life of our nation. The expansion of these ideas is the gospel of the American university."

References

1. C. R. Mann, "A Study of Engineering Education," The Carnegie Foundation for the Advancement of Teaching, *Bulletin* No. 11, 1918, Chapter 1.
2. University of Illinois Register, 1919-20, page 46.
3. University of Illinois Directory, 1916, page XXIV.
4. University of Illinois Alumni Record, 1918, page X.
5. Reference No. 1, page 89.
6. Reference No. 1, page 24.
7. "Report of Committee on Admissions and Eliminations of Engineering Students," Society for the Promotion of Engineering Education, *Journal* of *Engineering Education*, September 1925, page 66.
8. W. E. Wickenden, "Do We Need Better Engineering Education?," McGraw-Hill Book Notes, February 1926, page 1.
9. W. H. Timbie, "Cooperative Course in Electrical Engineering of the Massachusetts Institute of Technology," JOURNAL A. I. E. E., June 1925, page 613.

10. The Evolution of Engineering, president's address, H. S. Stott, Trans. A. I. E. E., Vol. XXVII 1908, pp. 459-464.
11. Reference No. 1, pages 106 and 107.
12. Reference No. 1, page 88.
13. "A Study of Enginering Graduates and Former Students, Non-Graduates," *Journal* of *Engineering Education*, December 1925, page 290.
14. Ditto, page 265.
15. Stanford University Register, 1924-25, pages 119 and 120.
16. Herbert C. Hoover, "The Engineer's Place in the World," an address before American Engineering Council, *Engineering News-Record*, January 24, 1924, page 160.
17. F. C. Pratt, "Relation of Engineering Education to Industry," *Journal* of *Engineering Education*, October 1925, page 137.
18. F. C. Pratt, "Professional Engineering Education for the Industries," *Bulletin* of Society for the Promotion of Engineering Education, January 1922, page 229.
19. Edward Bennett, contribution to discussion, Report of Bell System Educational Conference, 1924, page 126.
20. F. L. Bishop, "Education Versus Training," McGraw-Hill Book Notes, May 1924, page 1.
21. F. B. Jewett, Report of Bell System Educational Conference, 1924, page 195.
22. John Mills, "Selecting and Placing College Graduates in Business," a paper presented before American Management Association, pages 3 and 4.
23. M. I. Pupin, extract from Charter Day address at University of California, March 26, 1926, Journal A. I. E. E., April 1926, page 321.

Instruments and Measurements

Report of Committee on Instruments and Measurements*

A. E. KNOWLTON, Chairman

To the Board of Directors:

The Committee on Instruments and Measurements undertook to continue this year two of the studies begun in 1924 and to start a third major study.

Power and Energy Measurement

One of the first two was that of the measurement of energy and power under the following conditions:

1. A study of methods of measurement of variable power, with particular regard to cases of commercial importance, such as efficiency tests on large machines.
2. A study of methods of measurement of energy in large blocks where the high value of the product makes every practicable improvement of the method desirable.

The subcommittee originally consisted of H. B. Brooks, Chairman, F. V. Magalhaes, and J. R. Craighead; because of weight of other business, Mr. Brooks resigned as chairman and Mr. Craighead was appointed chairman, and G. A. Sawin added to the committee. It was decided that, in both problems, great advantage could be secured by improvement in watthour meters and the subcommittee took the first steps toward accumulating data on the present performance of watthour meters as a basis upon which to proceed. The presentation in February, 1925, of the paper by Messrs. Kinnard and Faus on *Temperature Errors in Induction Watthour Meters* indicated such an advance in the field of watthour meters that it was considered unnecessary to accumulate the data referred to above; this branch of the work was dropped, therefore, because that and other work now in progress makes it seem probable that meters of substantially improved accuracy, particularly with regard to errors with varying temperature, would be available.

In connection with the further study of the first problem, the paper by Mr. E. S. Lee, presented in May 1925, entitled *Measurement of Electrical Output of Large A-C. Generators*, covered to a satisfactory degree the necessary details of application of indicating instruments to the testing of variable power.

In the measurement of energy in large blocks, present commercial methods require the use of instrument transformers and watthour meters. Therefore, the subcommittee has prepared the following short discussion of methods and devices in use:

This discussion refers to the measurement of energy on three-phase circuits at large supply or interchange points, where the value of the energy is large enough to justify any reasonable complication or expense to improve the accuracy and certainty of measurement.

When power is measured in large blocks, the current and voltage are practically always of such values as to require instrument transformers, both for convenience in application to meters and instruments and for protection of operators. The systems are usually three-phase. Grounding conditions of the systems vary, but for metering purposes may be classified in three groups:

1. Ungrounded.
2. Having one or more grounds on only one side of the metering point.
3. Having grounds on both sides of the metering point or a fourth wire so that there is the possibility of currents passing the metering point outside the three-line conductors.

*Committee on Instruments and Measurements:

A. E. Knowlton, Chairman
F. V. Magalhaes, Vice-Chairman
H. B. Brooks, Secretary

O. J. Bliss,	W. M. Goodwin, Jr.,	H. A. Perkins,
Perry A. Borden,	C. M. Jansky, Jr.,	L. T. Robinson,
W. M. Bradshaw,	W. B. Kouwenhoven,	Bryon W. St. Clair,
J. R. Craighead,	P. M. Lincoln,	G. A. Sawin,
W. A. Del Mar,	W. M. McConahey,	I. B. Smith,
E. D. Doyle,	W. J. Mowbray,	Roy Wilkins.

Presented at the Annual Convention of the A. I. E. E. at White Sulphur Springs, June 21-25, 1926.

1. *Ungrounded Systems.* The usual form of metering is by the use of two potential and two current transformers with a polyphase meter shown in Fig. 1. The advantages lie in the fact that there are only four transformers and one meter to care for, and that the meter will rotate forward under all conditions where the energy flow is in a given direction. The disadvantages lie in the necessity of having elements with closely similar characteristics and with negligible interference, and in the fact that the power factor under which the elements actually operate differs from the line power factor due to the use of voltages which in a balanced circuit are dephased 30 deg., one in the lagging and one in the leading direction from the position representing the true power factor of the three-phase circuit. For this use, therefore, the meter selected should have:

a. Close balance of elements and negligible interference between elements.

b. Excellent power-factor characteristics.

The substitution of two single-phase meters for the polyphase meter is sometimes advocated. This does not change the situation in regard to power factor, but substitutes the adjustment of the two meters for the balance of elements. Where the effect of low power factor or of unbalance of load at somewhat higher power factors causes one meter to run backward, the system will be in error due to the light load adjustment on the reversed meter, which will produce torque in the wrong direction. This may be met by the use of separate meters to record the backward reading, with a ratchet arrangement which allows each meter to record energy delivered in one direction only, as has been done in cases where the direction of the total flow of energy is expected to reverse at intervals. The polyphase meter is usually considered preferable.

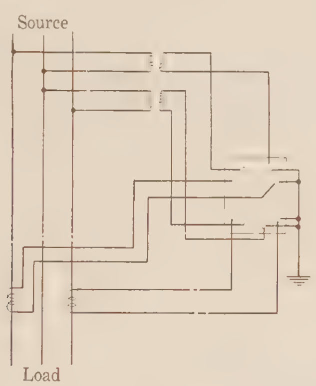

Fig. 1—Connection for Metering on Three-Wire, Three-Phase System with not more than One Point Grounded.

2. *Systems having grounds on one side of the metering point.* These may be treated as ungrounded systems, using the methods described above, or the system shown in Fig. 2 may be used. Here three potential transformers are connected with primaries in *Y*, the common point grounded, and three current transformers are used with a three-element, polyphase meter, or with three single-phase meters. The three-element, polyphase meter has the advantage of simplicity as compared with the three single-phase meters, but it should be assured that interference between elements is negligible and that a satisfactory balance between elements is assured; once obtained, the balance among elements is quite permanent, while the balance among the three single-phase meters is subject to the usual small variations requiring occasional adjustment.

This method has the advantage of having the power factor of each element of the three-phase meter, or of each single-phase meter, the same as the line power factor on a balanced circuit, approaching the line power factor under unbalanced conditions more closely than the methods previously described.

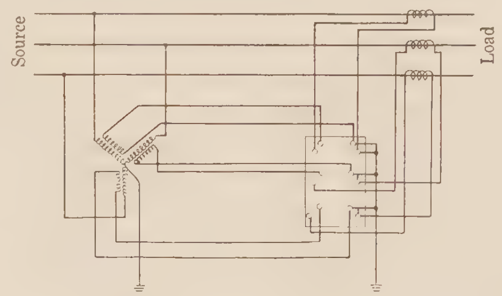

Fig. 2—Connections for Metering on Four-Wire, Three-Phase System or Three-Wire, Three-Phase System with Ground on Both Sides of the Metering Point

To secure good results, it is necessary that the grounding of the primary circuit be sufficient to maintain the neutral at a satisfactory balance at all times among the three phases. If this is not accomplished, the voltages on the individual potential transformers vary with circuit conditions and with the characteristics of the potential transformers themselves, involving certain errors in the potential transformer ratio and phase angle and in the meters.

In some cases this method has been proposed for application to ungrounded circuits, but the uncertainty of the position of the neutral renders it unsatisfactory for the best accuracy. For other reasons it is undesirable also to ground the neutral of the primaries of the potential transformers when the circuit is not otherwise grounded. It is possible to omit the ground on the potential transformer primary and obtain an artificial neutral by balancing the secondary burdens of the potential transformers, but the method requires care in adjustment and therefore, is not to be recommended.

3. *Systems having grounds on both sides of the metering point, or a fourth wire.* These systems should be treated as four-wire, three-phase systems, using the method shown in Fig. 2. In the unlikely case of an ungrounded, four-wire, three-phase system, the common point of the potential transformer primaries should be connected to the fourth wire.

In some cases, switching operations under different

conditions of load and supply cause important variations in the ground connections. Here the following two fundamental principles govern the method selected:

a. The minimum number of current transformers and corresponding meter elements must be such that under any condition, where a correct record is desired, no more than one possible path for return current past the metering point shall be without a transformer and meter element; in other words, in the circuit of n wires or paths, the minimum number of current transformers and corresponding meter elements required is $(n-1)$.

b. The connection of potential transformers must be such that the unbalance of voltages on their primaries is not in excess of the unbalance of the delta voltages on the primary lines.

In illustration of the first principle, consider a three-phase, three-wire circuit, having a permanent neutral ground on one side of the metering point and an occasional neutral ground on the other; the connection of Fig. 1 cannot be properly used because of possible ground current past the metering point during the presence of the second ground but the connection of Fig. 2 is correct.

An illustration of the second principle: Suppose that, at times, the entire circuit is ungrounded; if the connection of Fig. 2 is used, the voltages on the potential transformers will be subject to unbalance because the relation of the various lines to ground is no longer definitely controlled. Assuming the practise once used in emergency of disconnecting the system ground to continue operation when one line is grounded be followed, two transformers will receive delta voltage and the third transformer no voltage. In this case, the ground must be removed from the potential transformer primary neutral and a voltage balance be obtained by adjusting secondary burdens. These latter practises have been recognized as harmful for other reasons as well, and they are practically obsolete for the type of circuits under consideration. They are mentioned as an illustration of an extreme case only.

Selection of Instrument Transformers

The errors of an instrument transformer appear as an error of ratio and as a phase angle by which the secondary voltage or current departs from its theoretically correct phase for metering. Since the rate of the watt-hour meter and its lag are both adjustable, it is possible to offset known errors, to some extent, by special adjustment of the watthour meter. Since, however, the ratio and phase angle of ordinary instrument transformers vary appreciably with voltage, current, burden, etc., any adjustment of the watthour meter to meet these errors is based upon an estimated average condition and therefore cannot be very accurate. It is, therefore, desirable to select transformers and adjust conditions to give the best possible accuracy without corrective adjustment of the watthour meter. This applies particularly to phase-angle errors of which the variation with power factor makes satisfactory correction impracticable.

Potential Transformers

Standard commercial potential transformers are designed to cover a range of burdens. In the higher voltage sizes, used on most circuits of large power, the accuracy is usually somewhat better than on low-potential transformers. The no-load phase angle is ordinarily negative (secondary voltage reversed leading primary voltage), and several types of transformers are available where this does not exceed 8 minutes at 60 cycles. Non-inductive current drawn from the secondary windings tends to change this angle in the positive direction and lagging current in the negative direction. In the best transformers, it is possible, by increasing the non-inductive current, to reduce the phase angle practically to zero by proper adjustment of

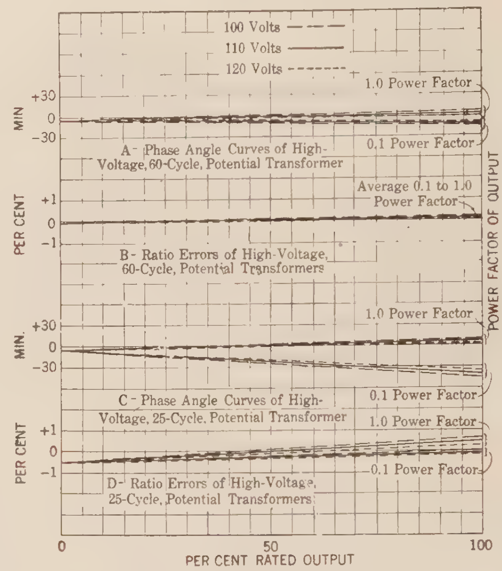

Plate 1—Ratio Error and Phase-Angle Curves of High-Voltage 25- and 60-Cycle Potential

the secondary burden. Even without this adjustment the phase angle with two watthour meters and necessary leads as sole burden may generally be kept within 10 to 12 minutes at 60 cycles.

The no-load ratio is usually low, but this error in many high-voltage transformers is not more than 0.2 per cent at 60 cycles. Either non-inductive or lagging current drawn from the secondary tends to increase ratio, so that frequently the reduction of phase angle by burden adjustment referred to above is accompanied by an increase in accuracy of ratio. The variation in errors of a potential transformer for changes of voltage within the limits caused by ordinary regulation is very small. Whatever ratio error remains may, therefore, be fairly considered a constant error subject to correction by compensation in the watthour meter or by the application of a correction to the final result.

Plate 1, a and b, show average ratio errors and phase

angles of a number of transformers from 22,000 to 66,000 volts at 60 cycles, and c and d show test results on a single 33,000-volt transformer at 25 cycles.

Current Transformers

Standard current transformers are designed to cover a range of burdens. The ratio errors and the phase angle between primary and (reversed) secondary currents vary appreciably with current, secondary burden and large changes of frequency. The phase angles are usually positive, and are increased by increase in non-inductive burden. It is desirable, therefore, to keep both burden and its power factor as low as possible. This means low resistance leads and only the necessary one or two watthour-meters for the best results. The variation of ratio and phase angle with current must also be considered. It is desirable to obtain transformers having as little variation of these errors with current as possible.

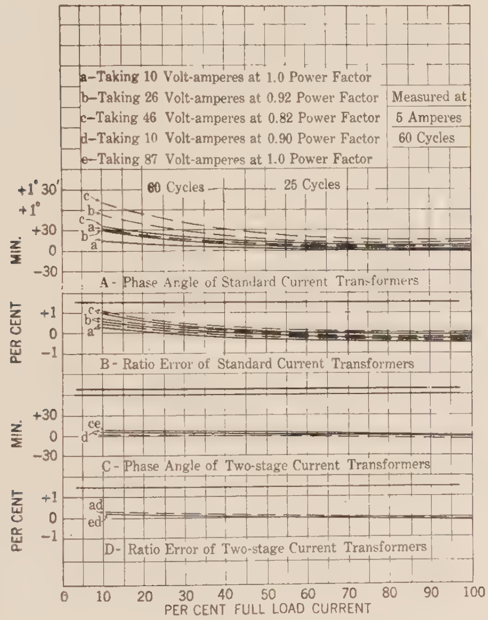

Plate 2—Ratio Error and Phase-Angle Curves of Standard and Two-Stage Current Transformers at 35 and 60 Cycles, with Stated Burdens

On account of the range for which the transformer is designed, the ratio is usually low at low burdens to prevent it from being too high for reasonable accuracy at high burdens. The amount by which the ratio is low on the lowest practicable burdens varies with the practise of the various manufacturers, but does not usually exceed 0.8 per cent maximum. No attempt should be made to bring a low ratio up by additional burdens, as it requires very careful adjustment of the amount and power factor of the burden to produce satisfactory results on ratio and phase angle at a single value of current, while the resulting phase angle (and sometimes ratio) at other values of current becomes rapidly worse. This difference between treatment of potential and current transformers should be noted as resulting from the fact that the potential transformer must be accurate at a roughly constant voltage and current, while the current transformer must be accurate at widely varying currents and voltages. The same results may be obtained by adjustment of the watthour-meter as by a change in the ratio of the current transformer.

Improvement of current-transformer accuracy by special means has been proposed in several forms. A method recently brought out, for which apparatus is beginning to be available, is the two-stage transformer with special watthour-meter. ("The Two-stage Current Transformer," Brooks and Holtz, A. I. E. E. Journal, June 1922.) The two-stage transformer is, in principle, a combination of two transformers in one, in which the second transformer corrects the errors of the first by the use of a simple corrective winding in the watthour-meter. By this arrangement the errors of ratio and phase angle due to the current transformer are greatly decreased as compared with standard current transformers. Typical curves show ratio error held within 0.2 per cent and phase angle within about 6 minutes for a test from 10 per cent to 100 per cent current at 60 cycles with a burden of two watthour-meters in the corrected circuit.

In Plate 2, A and B show average ratio errors and phase angle at 25 and 60 cycles of standard current transformers, and C and D show test results on a two-stage transformer designed for a working pressure of 32,000 volts.

Secondary Connections of Instrument Transformers

To assure the best results, it is preferable that separate leads be used for all secondary circuits, and that the length of leads be kept as short as possible. All secondary circuits of current and potential transformers should be connected to a common ground.

Watthour Meter

The watthours per disk revolution of a watthour-meter will depart somewhat from the nominal value for load current values other than those for which it has been adjusted. On this variation are superposed whatever errors result from changes of temperature, power factor, frequency, voltage and wave form. Certain work now in progress (such as that of Kinnard and Faus, already cited) makes it seem probable that meters of substantially improved accuracy, particularly with regard to errors with varying temperature, are to be available. Temperature compensation is more readily obtained for meter elements operating at unity power factor; inasmuch as one of the two elements of the ordinary polyphase meter usually operates at low power factor, it is greatly to be desired that such studies be prosecuted with a view to obtaining temperature compensation for all conditions of phase departure within the meter elements.

The power-factor error is partly compensated by lag adjustment. The frequency and voltage errors are negligible for the variations occurring in the usual circuits under operating conditions. If special wave-form conditions, serious enough to cause error, exist, the greater part of the error may be eliminated by calibrating the watthour-meter in place by the use of indicating instruments the wave-form error of which is negligible.

The watthour-meter in general service is one of the most reliable devices in measurement work. In view, however, of the large value of the energy measured at the points here under consideration there are cases where it may be advantageous to use two watthour-meters similarly connected to assure a proper record in case of the accidental failure of one meter. In such cases it is proper to designate one meter as the regular standard, and to substitute the reading of the second meter only when reasonable proof of the failure of the first meter to record correctly has been obtained.

Owing to the recent rapid improvement in the watt-hour-meter, detailed data on performance is omitted.

High Frequency Measurements

The second of the studies undertaken in 1924 was in the field of measurement of high-frequency quantities; progress is being made in this investigation but the subcommittee (C. M. Jansky, Chairman, E. D. Doyle, B. W. St. Clair) makes no report at this time.

Dielectric Losses and Power Factor

The matter of measurements in connection with dielectrics, especially solid dielectrics, was surveyed by the committee and a subcommittee appointed as follows: W. A. Del Mar, Chairman, O. J. Bliss, and W. N. Goodwin, Jr. This committee arranged a symposium of papers presented at the First District Regional Convention at Niagara Falls May 26, 27, 28, 1926. The papers submitted are as follows:

The Power Factor of Dielectrics and Insulation, by J. B. Whitehead, Johns Hopkins University

The Mechanism of Breakdown of Dielectrics, by P. L. Hoover, Harvard University

Standards for Measuring Power Factor of Dielectrics, by H. L. Curtis, Electrical Testing Laboratories

The Significance of Errors in Dielectric-Loss Measurements, by C. F. Hanson, Habirshaw Electric Cable Co.

Use of Dynamometer Wattmeter for Measuring Dielectric Power Loss, by E. S. Lee, General Electric Co.

Commercial Dielectric-Loss Measurements, by R. E. Marbury, Westinghouse Elec. & Mfg. Co.

Three Methods of Measuring Dielectric Power Loss and Power Factor, by E. D. Doyle and E. H. Salter, Electrical Testing Laboratories

Compensation for Errors of the Quadrant Electrometer, by D. M. Simons, Standard Underground Cable Co.

The Dielectric-Loss-Measurement Problem, by B. W. St. Clair, General Electric Co.

Zero Method of Measuring Power with a Quadrant Electrometer, by W. B. Kouwenhoven and P. L. Betz, Johns Hopkins University

It is believed that these papers in the total give a reliable index of the present state of the art of measurements involving the higher voltages and small phase angles.

TIDE-POWER DREAMS ARE COMING TRUE

The flow of tides may yet generate a large amount of electric power. This type of project, for years held to be fanciful, is about to get a real start on the international boundary between Maine and New Brunswick. The Federal Power Commission recently granted Dexter P. Cooper a preliminary permit covering a proposed huge development of tidal power in Passamaquoddy and Cobscook Bays, Washington County, Maine. The next step is to secure the same sort of permit from the Canadian government.

On May 27 the private bills committee of the Canadian House of Commons approved the bill to permit Mr. Cooper's plan to be carried out, but added a number of amendments as the bill went to the House for action. One of these provides the Dominion authorities must be satisfied with the allocation of power as between the United States and Canada before the project begins to operate. Other amendments require that a majority of the directors be British subjects and that not more than ten million dollars of bonds be issued.

Mr. Cooper purposes to build a series of dams between various islands and the Canadian and American mainlands so as to trap vast volumes of water in two great pools at a coastal point where the ebb and flow of the Atlantic Ocean tides are strong. Water is to be admitted through 43 gates during the hours that the tide is rising and to be discharged steadily through one or more great electrical generating stations.

The calculations are to obtain a mean operating head of 13 ft. between the two pools created by natural barriers and the dams. A flow of 300,000 second-feet will be counted upon to develop two and a half million kilowatt-hours of electric energy annually through the operation of generators of 600,000 horsepower capacity. There are few electric generating stations in the world with so large a capacity for producing current for electric light and power. The principal market for this power will be down the Maine and Massachusetts coasts to Boston.

Stability Characteristics of Alternators

BY O. E. SHIRLEY[1]

Associate, A. I. E. E.

Synopsis.—During the past few years, stability characteristics of systems using long lines have been discussed at considerable length, but not so much attention has been given to the characteristics of the load. This paper shows that power limits may be reached with very short lines and certain classes of load.

The characteristics of several classes of load, such as motors of various kinds with constant shaft output, variable impedance loads (synchronous converters for railways), constant impedance, and miscellaneous combinations, are discussed as they affect the stability of the generator. The criterions for the stability of an alternator as developed by this paper are "short-circuit ratio," saturation, power factor of the load, and character of the load.

A series of curves and a formula for the minimum allowable value of short-circuit ratio as a function of saturation and power factor are proposed for general purpose alternators which may be called upon to deliver power to any of the various classes of load. These curves are derived from characteristic curves of typical machines.

It is not intended that these curves shall be used for generators which supply power over long transmission lines, as the characteristics of these lines may require considerably higher values of short-circuit ratio, and the generator must be specially designed to meet the individual requirements.

* * * * *

FOR the past few years, the problem of power limits and stability of alternators has been given considerable attention especially from the standpoint of transmission over lines of lengths approaching the maximum economical distances. The effect of exciter stability, the possibilities of automatic voltage regulators, and compensation for armature reaction by compounding through rectifiers have all been quite fully presented. That there are practical limits for stability in operation for certain classes of load, even with short lines, has been suggested in some papers and discussions, but usually as incidental only to the presentation of other features which were covered much more completely.

The purpose of this paper is to discuss the characteristics of the various classes of load, and to propose a set of curves based on the inherent characteristics of a-c. generators to secure a practical degree of stability with the kinds of load for which this factor must be considered, to secure successful operation. These curves are intended for machines operating under ordinary conditions with comparatively low line drop, and will not be applicable for those operating with very long, high-voltage transmission lines.

In recent years the tendency in the design of alternators has been to decrease the short-circuit ratio, that is, the ratio of field current for normal voltage on open circuit to the field current for rated stator current on short circuit. In many cases this short-circuit ratio may go to extremely low values without serious consequences, aside from poor regulation, but with some kinds of load, an alternator with a short circuit ratio very much below unity may not carry swings appreciably above full load and the voltage will "fade" so that part of the load will be dropped. Such a disturbance may be very puzzling to the operator, as the generator will dip in voltage, dropping a considerable part of the load which caused the instability (due to operation of low-voltage relays), and the voltage will then recover to approximately normal. The machine may then operate as though nothing had happened, unless the maximum load for stability is again exceeded. The fading of voltage, or instability, results from a combination of characteristics of machine, line and load. The principal factors determining stability of the alternator are degree of saturation, power factor of load, and short-circuit ratio. For any particular class and power factor of load, and for alternators with the same degree of saturation, there will be a minimum value of short-circuit ratio which is the lower limit for design of these machines if they are to carry full load with the necessary margin in stability. This margin in stability is necessary to enable the machines to carry the ordinary swings in load successfully.

The degree of saturation in the alternator may be represented by the "saturation factor" as defined in the A. I. E. E. Standards.

Curves showing the proposed minimum values of short-circuit ratio for various lagging power factors and saturation factors are derived in this paper by combining load and generator characteristics.

Load Characteristics

1. *Constant Power Output.*

a. Induction motors with practically constant shaft output, such as those driving fans, pumps, compressors, direct-current generators, etc.

b. Synchronous motors for same classes of service as "a."

2. *Variable Impedance.*

a. Synchronous converters supplying power to series motors for railway service.

3. *Constant Impedance.*

a. Light and heating.

b. Electric furnaces, welders, etc.

c. Synchronous converters for lighting load.

4. *Miscellaneous.*

Combination of constant power, variable impedance, and constant impedance loads.

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To be presented at the Pacific Coast Convention of the A. I. E. E., Salt Lake City, Utah, Sept. 6-9, 1926.

Constant Power Output. Figs. 1A and 1B represent diagrammatically alternators furnishing power to a synchronous motor load and an induction motor load, respectively.

The curves in Fig. 2 show the variation in power factor with voltage for synchronous and induction motors having constant shaft output. The synchronous motor curves are based on adjusting the motor field currents for rated power factors at normal voltage and holding these motor field currents constant for other voltages. The induction motor curve is based on operation at 90 per cent power factor at normal voltage and load. Curves showing variation of current with voltage corresponding to these power factor curves are given in Fig. 3.

The alternator characteristics are represented by the

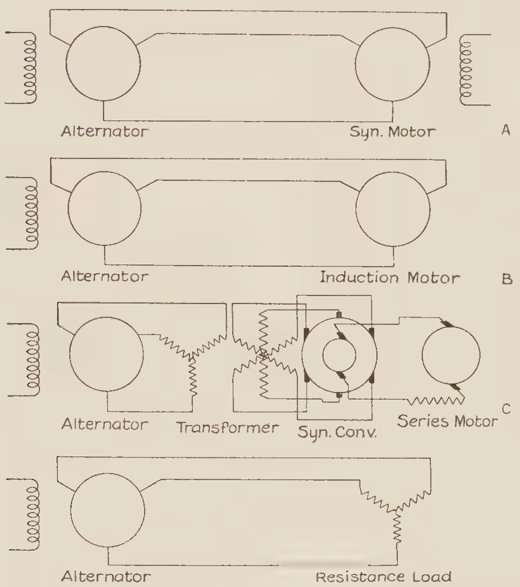

Fig. 1—Diagrams for Various Classes of Load

usual open circuit saturation and synchronous impedance curves. It is possible to design machines with a very wide range of characteristics, but, for the purpose of illustrating the combination of machine and load characteristics, curves for a general purpose alternator with fairly high saturation have been selected.

The values of alternator excitation required with constant power output for a number of voltages, above and below normal, were calculated for the different classes of motors represented in Fig. 2, for the stator currents Fig. 3.[2] Refer to Fig. 5 for these curves. They show that excitation decreases slowly with the voltage to a minimum point and then increases again. The minimum excitation and the corresponding voltage determine the limit of steady-state, stable operation. Refer to Fig. 5, Curve *B*. If the generator excitation corresponds to 92 per cent voltage, and the voltage starts to decrease, due to addition of a very small increment of load, the excitation required at a slightly lower voltage will be less than that actually on the machine, and the voltage therefore will be stable. However, if the excitation is decreased to that required for 88

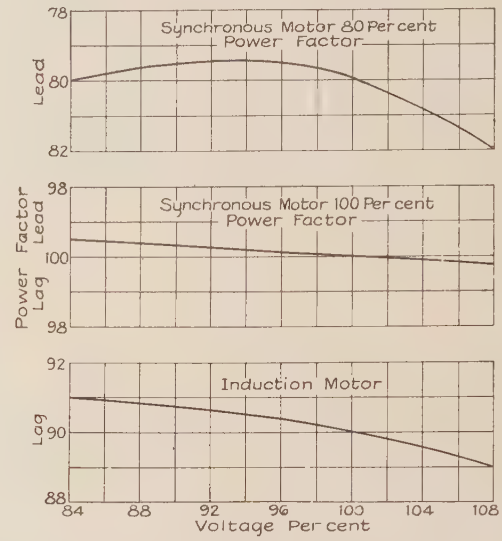

Fig. 2—Variation of Power Factor with Voltage. Constant Power Output

per cent voltage, and the small increment of load is added, the voltage will start to decrease and it will then pass through no value for which the excitation is

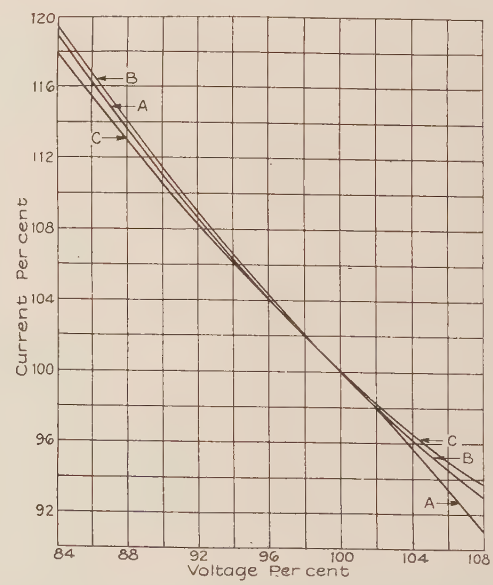

Fig. 3—Variation of Alternator Current with Stator Voltage. Constant Power Output

A. Synchronous motor—80 per cent, power-factor lead at normal voltage
B. Synchronous motor—100 per cent, power factor at normal voltage
C. Induction motor—90 per cent, power-factor lag at normal voltage

sufficient. The voltage will continue to drop until the generator and motors pull out of step.

The curves in Fig. 5 show quite clearly the behavior of an alternator with motor load having constant shaft output, but the maximum power output of the generator

2. *Reactance*, Appendix C., Doherty and Shirley, A. I. E. E. Transactions, Vol. 37, Part 2, p. 1293.

may be determined more simply by a method which has been used in various forms for several years.[3]

The curve between current and voltage at a given power factor and for a constant excitation current is obtained by calculation or test. These curves, calculated for normal load excitation and at the power factor

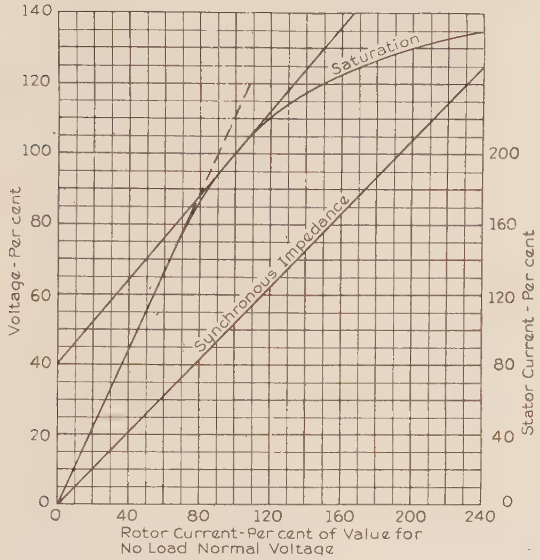

FIG. 4—CHARACTERISTIC CURVES OF ALTERNATOR

Saturation factor—1.65 at normal voltage
Short-circuit ratio—1.04
Stator reactance—18 per cent

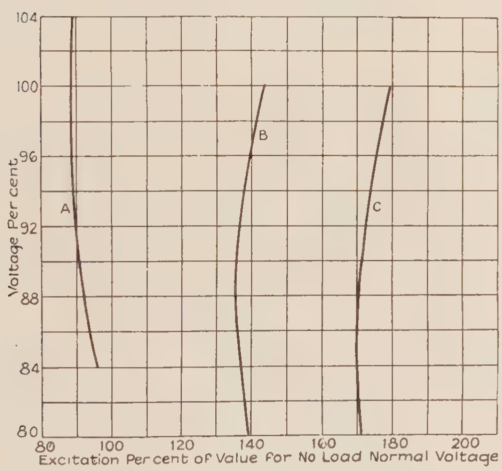

FIG. 5—ALTERNATOR EXCITATION—VOLTAGE CURVES CONSTANT POWER OUTPUT

A. Synchronous motor—80 per cent, power-factor lead at normal voltage
B. Synchronous motor—100 per cent, power factor at normal voltage
C. Induction motor—90 per cent, power-factor lag at normal voltage

for normal voltage of each of the classes of motor load in Fig. 3, are shown in Fig. 6. The kv-a. output curves, derived from these curves, are also given in Fig. 6.

3. *Elements of Alternating Currents*, Franklin and Williamson, The MacMillan Company, 1901, p. 124.

"Alternating Current Generators," W. J. Foster, *General Electric Review*, June 1923, Vol. 26, p. 365.

A. I. E. E. Discussion, C. A. Nickle, TRANSACTIONS A. I. E. E., Vol. 43, p. 89.

The voltages for the maximum kv-a. points in Fig. 6 correspond very closely to the voltages for the minimum excitation points in Fig. 5. The curves do not check exactly, because in Fig. 5 the effect of varying power factor is taken into account, and in Fig. 6, constant power factor is assumed. The difference between the two methods is very small, as will be explained later in connection with Fig. 9.

The behavior of an alternator with increasing load at constant power factor is represented by current-voltage and kv-a-voltage curves at excitations corresponding to 80-, 100-, 120-, and 140-per cent load at normal voltage (See Fig. 7). The kw. load, expressed as a per cent of the kv-a. rating, is also given by the dotted curves for comparison. These curves show that the maximum kv-a. points occur at voltages increasing up to a certain value and then decreas-

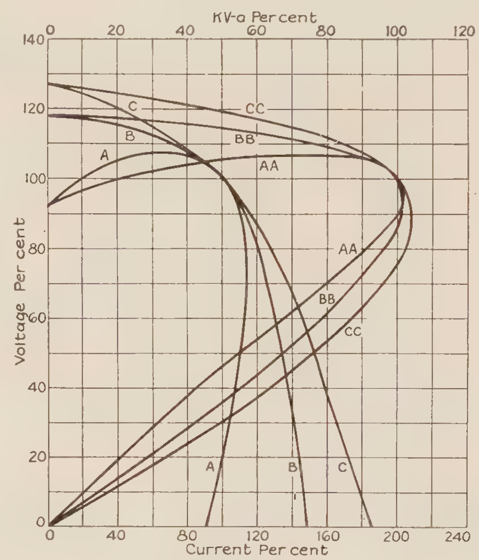

FIG. 6—ALTERNATOR CHARACTERISTICS—CONSTANT EXCITATION

Saturation factor—1.65
Stator reactance—18 per cent
Short-circuit ratio—1.04
Current-voltage curves *A*—*B*—*C*
Kv-a.-voltage curves *A A*—*B B*—*C C*

A—*A A* 80 per cent power-factor lead
B BB 100 per cent power factor
C—*C C* 90 per cent power-factor lad

ing, so that the load will not be reached under practical operating conditions where the machine will be unstable at normal voltage. The curves also indicate that alternators with high saturation would operate at very high loads without becoming unstable, but practical experience has shown that it is necessary to maintain a considerable margin in voltage above the minimum point, and in kv-a. below the maximum point.

In Fig. 9, curves *A* and *A A* are calculated for normal load excitation at 90 per cent power-factor lag; curves *B* and *B B*, for 91 per cent power factor; and curves *C* and *C C*, for 89 per cent power factor. The dotted curves, *D* and *D D*, take into account the variation of power factor with voltage for the induction motor represented in Fig. 2. These curves show that the maximum kv-a. for operation at variable power factor,

such as that with induction-motor load, is very closely approximated by the curve of kv-a. for normal power factor.

The curves in Fig. 7 show clearly the importance of keeping up the excitation so as to maintain normal voltage with this class of load. This result may be secured with hand regulation by operating with excitation corresponding to normal load and voltage, which will give a voltage above normal when the load is lower than the machine rating. A regulator is very effective in maintaining stability up to the steady state maximum capacity of the alternator at normal voltage, but if the load exceeds this maximum value, the use of any of the

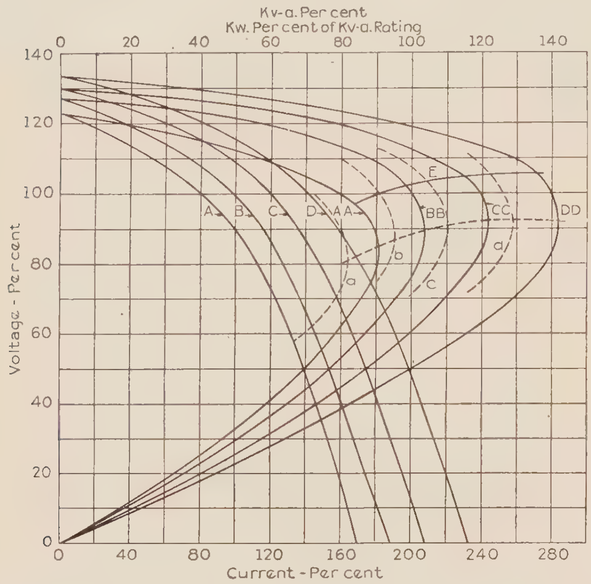

FIG. 7—ALTERNATOR CHARACTERISTICS—CONSTANT EXCITATION

Saturation factor—1.65 | A—A A—a 80 per cent kv-a. at normal voltage
Stator reactance 18 per cent | B—B B—b normal kv-a. at normal voltage
Short-circuit ratio 1.04 | C—C C—c 120 per cent kv-a. at normal voltage
Power factor—90 per cent lag | D—D D—d 140 per cent kv-a. at normal voltage

E. Kv-a.-voltage curve for 15 per cent margin in voltage above maximum kv-a. points

Current-voltage curves *A, B, C, D*

Kv-a.-voltage curves *A A—B B—C C—D D*

Kw.-voltage curves *a, b, c, d*

present standard regulators will not maintain stability. If, however, the load conditions are such that the maximum load is exceeded only slightly, stable operation may be obtained by regulating for a voltage a little over normal, provided the machine will not be injured by the higher voltage operation.

The maximum kv-a. values given by the excitation curves do not include any allowance for the effect of the lines and the connecting apparatus, or swings in load, and practical operation will require a margin in the maximum capacity of the alternator to take care of these factors. The required margin is a point that must be determined largely from operating experience.

The more important characteristics of the alternator which affect stability are saturation, relation of no-load field strength to armature reaction, and power factor.

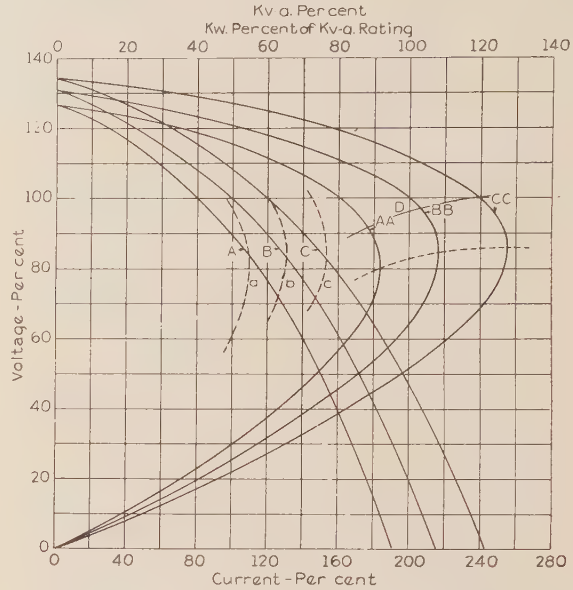

FIG. 8—ALTERNATOR CHARACTERISTICS—CONSTANT EXCITATION

Saturation factor—1.65 | *A—A A—a*, 80 per cent kv-a. at normal voltage
Stator reactance 18 per cent | *B—B B—b*, normal kv-a. at normal voltage
Short-circuit ratio 1.04 | *C—C C—c*, 120 per cent kv-a. at normal voltage
Power factor—60 per cent lag

D. Kv-a.-voltage curve for 15 per cent margin in voltage above maximum kv-a. points

A, B, C current-voltage curves

A A—B B—C C kv-a.-voltage curves

a, b, c kw.-voltage curves

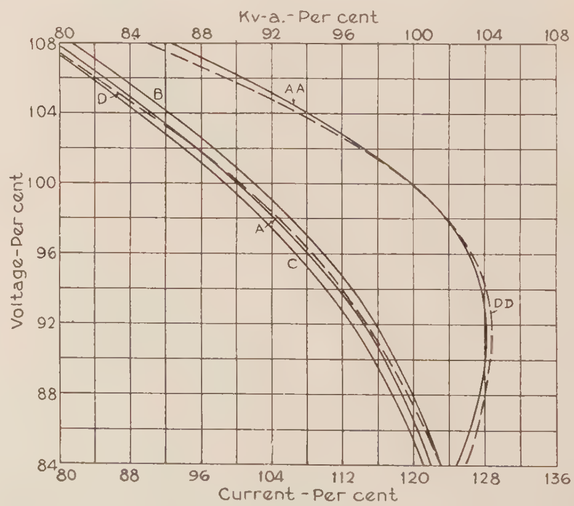

FIG. 9—ALTERNATOR CHARACTERISTICS—CONSTANT EXCITATION. EXCITATION HELD AT VALUE FOR NORMAL KV-A. AT RATED VOLTAGE AND 90 PER CENT POWER FACTOR

Saturation factor 1.65 | *A—A A* 90 per cent power factor
Stator reactance 18 per cent | *B* 91 per cent power factor
Short-circuit ratio 1.04 | *C* 89 per cent power factor

D—D D power factor varying between 89 per cent at 108 per cent voltage and 91 per cent at 84 per cent voltage

A—B—C—C current-voltage curves

A A—D D kv-a.-voltage curves

It is proposed that the saturation factor, as defined by the A. I. E. E. Standards and the short-circuit ratio,

be used as the criterion of stability for an alternator at any given power factor. The relation of these two factors for obtaining a consistent margin in stability for synchronous-motor or induction-motor load at different power factors is worked out in a later section of this paper.

The problem of stability with long high-voltage lines and power transmission approaching the maximum line capacity requires a very large increase in stability of the generators and receiving apparatus. A considerable number of papers dealing with this subject have been presented to the Institute, and no attempt is made in this paper to cover this problem.

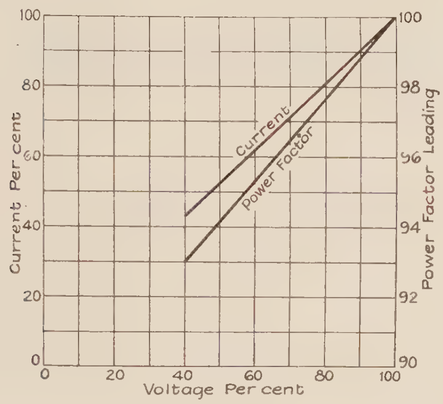

Fig. 10—Synchronous Converter Characteristics Series Motor Load

D-c. current assumed to vary directly with d-c. voltage.

Curves showing variation of current and power factor on high-voltage side of transformer with voltage on high-voltage side of transformer

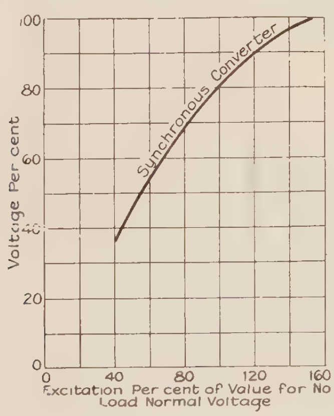

Fig. 11—Alternator Excitation—Voltage Curves

Synchronous converter with characteristics on Fig. 9

Variable Impedance Load. A synchronous converter furnishing power to series railway motors is an example of a load with quite different characteristics from the one just discussed. For simplicity in working out the curves, the current on the d-c. side of the converter is assumed to vary directly with the voltage. The power factor on the high-voltage side of the transformer will remain quite close to unity due to the converter being self-excited. The current and power-factor curves are drawn as straight lines, and will approximate the actual conditions quite closely. Fig. 10 shows the assumed curves and Fig. 11 is the corresponding excitation-voltage curve. It will be noted that the excitation continues to decrease with the voltage, instead of having a minimum point as with induction or synchronous motor load.

The stability of the alternator is not a practical factor in a design for this class of load. It is therefore possible to use a machine with a short-circuit ratio of unity to carry very high short-time overloads (one to five minutes) on synchronous converters without trouble from instability, provided the alternator field is increased with load by automatic regulation.

The characteristics of a converter with lighting load are very similar to those just given, and the point of instability is not within the operating range of voltage, but very far below normal. It is possible, by hand or automatic regulation, to maintain normal voltage for any excitation within the heating limits of the rotor winding, and to carry any ordinary swings of load.

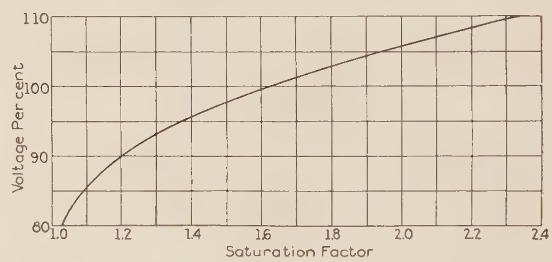

Fig. 12—Alternator Characteristics

Variation of saturation factor with voltage—saturation curve from Fig. 4

Constant Impedance Load. The current in this case will vary directly with the voltage throughout the entire range of load, and the excitation-voltage curve will be almost identical in shape with Fig. 11. With this class of load, the alternator will operate stably at any point on the kv-a-voltage curve, and the load limit will again be determined by the heating characteristics of the machine.

Alternator Characteristics for the Usual Commercial Load. The usual commercial load is a combination of the various classes just discussed and the selection of the generator with the proper characteristics is largely a matter of judgment. The calculation of excitation voltage curves similar to Fig. 5, for various values of load of the same characteristics as the given load, will show whether conditions of instability will be approached sufficiently to be a factor in the design of the generating equipment.

The kv-a-voltage curves, Fig. 7, indicate the maximum capacity for load which is practically all Class 1, but if there is a considerable percentage from Classes 2 and 3, the alternator may operate successfully at voltages below the maximum kv-a. point.

This may be illustrated by an example: Assume operation at 90-per cent voltage, Fig. 7. The maximum kv-a. capacity with Class 1 load under this condition is 104-per cent kv-a. as indicated by the maximum point of curve, *BB*, but, with other classes of load, it would be possible to operate at any point on any of the curves. Combinations of all of these different classes of load will give load characteristics, so that stable operation may be obtained somewhat below the maximum kv-a. point on the kv-a. curves. Just how far below the maximum point stable operation can be secured depends upon the percentages of the different kinds of load.

Derivation of Curves for Short-Circuit Ratio

The saturation factors for several values of voltage, below and above normal, for the saturation curve in Fig. 4 are plotted as a function of voltage in Fig. 12. The kv-a. values for an operating margin of 15 per cent in voltage, as determined by Figs. 7 and 8, are also shown as a function of voltage in Fig. 13.

The short-circuit ratios for various machine ratings

TABLE I

CALCULATIONS FOR 90-PER CENT POWER FACTOR

Volts per cent	Kv-a. per cent	Current per cent	Open circuit field current per cent from Fig. 4	Short-circuit field current per cent from Fig. 4	Short-circuit ratio	Sat. factor
100	90	90	100	87	1.15	1.65
103	101	98	105	94	1.12	1.84
105	112	107	109	103	1.06	1.94
106	125	118	110	114	1.03	2.04

corresponding to the kv-a., and voltage values for 90-per cent power factor from Fig. 13, Curve *A*, are derived as shown in Table I, which also includes the

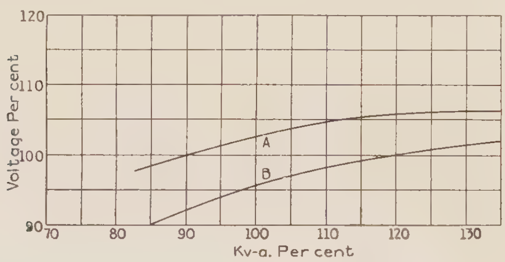

Fig. 13—Alternator Characteristics

Kv-a-voltage curves for 15-per cent margin in voltage—From Figs. 7 and 8

A 90-per cent power-factor lag
B 60-per cent power-factor lag

saturation factors for corresponding voltages taken from Fig. 12. Similar data were calculated also for the 60-per cent power factor, Curve *B* in Fig. 13. In Fig. 14, Curves *A* and *B* represent, graphically, the relations of short-circuit ratio and "saturation factor" as determined by these calculations.

The determination by trial of a simple formula to approximate these curves in the working range with reasonable accuracy, resulted in the following equation:

$$\text{Minimum } S\,C\,R = 1.4\sqrt{\frac{\text{Power factor}}{100\,F}}$$

Where minimum $S\,C\,R$ = minimum value of short-circuit ratio for rating to give a safe margin in stability for operation at normal rating and F = saturation fac-

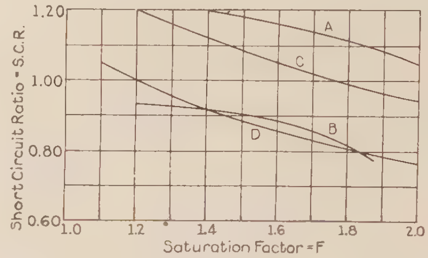

Fig. 14—Curves for Relation of Short-Circuit Ratio and Saturation Factor

From Figs. 12 and 13—(See Table I)

A 90-per cent power-factor lag
B 60-per cent power-factor lag

From formula $S\,C\,R = 1.4\sqrt{\frac{\text{Power factor}}{100\,F}}$

C 90-per cent power-factor lag
D 60-per cent power-factor lag

tor as defined by the A. I. E. E. Standards 7-59: "The saturation factor of a machine is the ratio of a small percentage increase in field excitation to the corresponding percentage increase in voltage thereby produced. Unless otherwise specified, the saturation factor of a machine refers to the no-load excitation required at rated speed and voltage."

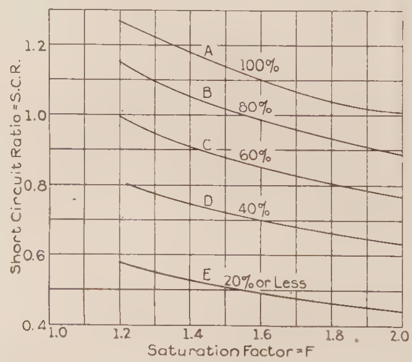

Fig. 15—Proposed Curves for Minimum Value of Short-Circuit Ratio of Alternators

A 100 per cent power-factor lag
B 80 per cent power-factor lag
C 60 per cent power-factor lag
D 40 per cent power-factor lag
E 20 per cent power-factor lag

From formula $S\,C\,R = 1.4\sqrt{\frac{\text{Power factor}}{100\,F}}$

The maximum allowable rating for any particular machine is determined by this minimum value of short-circuit ratio.

In Fig. 14, Curves *C* and *D* are derived from tish proposed equation, and a comparison with Curves *A* and *B* shows that for all practical purposes the equation will give the proper values of short-circuit ratio in the usual range of values of saturation factor.

Fig. 15 derived from the equation, covers the entire range of lagging power factors and the usual range of saturation factors. The equation will give results approaching zero as the power factor approaches zero, but since this is obviously impractical, the same values are proposed for power factors of 20 per cent or less. The curve covers lagging power factors only and no attempt is made to work out similar curves for leading power factor, since machines of this class are special and will come within the scope of the design of machines for very long transmission lines.

It will be noted that Fig. 15 gives the proposed minimum value of short-circuit ratio, and it is obvious that any machine with a higher short-circuit ratio will be satisfactory from the standpoint of stability.

Conclusions

Stability of operation of alternator depends on the characteristics of the load as well as on those of the alternator and line.

The minimum allowable value of short-circuit ratio for successful operation is determined by the character of the load, the saturation factor of the alternator, and the power factor. This assumes that the line drop is small enough to be covered by the proposed margin, which will usually be the case with general purpose machines.

When the character of the load is such that the current decreases with voltage, the stability characteristics will not be the determining factor in the selection of the proper value of short-circuit ratio.

The stability characteristics of an alternator for general service, when the load is predominantly motors with practically constant shaft output and line drop is not a serious factor, will be satisfactory with automatic regulation if the short-circuit ratio is not less than that given by Fig. 15.

When the load consists of a few comparatively large motors with swinging load, the proposed curves will give successful operation if the short-circuit ratio at a rating corresponding to the maximum load does not exceed the values indicated by the curves and automatic regulation is used.

Machines designed in accordance with these curves will operate successfully with hand regulation if the increments of load, due to adding more motors, are small enough to prevent excessive drop of voltage before the field rheostats can be adjusted to compensate for the added load.

The proposed values of short-circuit ratio are not applicable to generators for use with very long transmission lines, and the design of these machines is a special problem beyond the field of this paper.

Acknowledgments

In the preparation of this paper the author desires to express his appreciation of the assistance of Messrs. R. E. Doherty, C. A. Nickle, and R. H. Park.

Bibliography

Some Theoretical Considerat ons of Power Transmission Systems, C. L. Fortescue and C. F. Wagner, A. I. E. E. TRANSACTIONS, 1924, Vol. XLIII, p. 16-23.

Experimental Analysis af Stability and Power Limitations, R. D. Evans and R. C. Bergvall, A. I. E. E. TRANSACTIONS, 1924, Vol. XLIII, p. 39-58.

Discussion, A. I. E. E. TRANSACTIONS, 1924, Vol. XLIII, p. 70-103.

Fundamental Consideratians af Power Limits, R. E. Doherty and H. H. Dewey, A. I. E. E. JOURNAL, Vol. XLIV, p. 1045-1057, Oct. 1925.

Analytic Discussion of Some Factors Entering into the Problem of Transmission Stability, C. L. Fortescue, A. I. E. E. JOURNAL, Vol. XLIV, p. 951-961, Sept., 1925.

Discussion, A. I. E. E. JOURNAL, Vol. XLIV, p. 68-77, Jan., 1926.

"ELECTRIC LIGHT BED" CURE

Proceeding upon the theory that the dry heat of the sun ever since the creation has been nature's best curative agent and that the light and heat from ordinary electric lamps is the nearest artificial approach to it, Dr. Milton Fairchild of Chevy Chase, just outside of Washington, D. C., has built a long box in which are seven or eight house lamps. It is suspended over his bed by sash cord and window weights and can be drawn down over him leaving only his head protruding after he has turned in for the night. By a rheostat he can adjust the lamps to produce just the right degree of heat. He says it is a great success and that anybody can make one. Already 30 doctors of the Washington district agree with him.

ELECTRIC SHOVEL DIGS BACK TO DEVONIAN AGE

For generations fossil hunting has been a back-breaking process of laboriously picking and shoveling remains of prehistoric fauna out of rock and clay 'way out in a sun-baked desert. Today a huge electric shovel excavated fossilized fishes which lived in the Devonian period. It is doing this in a suburban region that some day will be overgrown by Cleveland and will be rendered forbidden ground for the excavations of paleontologists. The shovel is digging up geologic information by the ton, its electric power having removed all back-break from the process.

Vibration Recorder

For Electrically Measuring and Recording Small Mechanical Movements

BY A. V. MERSHON*

Associate, A. I. E. E.

General Description

THE vibration recorder was first designed to measure vibrations of rotating turbine wheels and the whipping of rotating shafts. The development of this instrument was necessary because ordinary hand micrometers or indicating devices could not be applied to the moving parts due to their inaccessible location.

Most of the parts in a steam turbine are made of iron or steel; therefore, the fundamental thought was to make use of magnetic flux changes to detect these vibrations. A bridge circuit was constructed having a test coil and a transformer coil as one arm, and a dummy coil and a duplicate transformer coil as the other arm. The dummy coil has an iron core with an adjustable air-gap, and the test coil has an iron core the air-gap of which varies with the vibration or motion to be recorded. Any unbalance of the magnetomotive forces produced by the currents in the two transformer windings gives a flux, which produces a voltage on a third winding connected directly to an oscillograph vibrator. An alternating current of approximately 500 cycles is used to excite this circuit.

The voltage of the internal or test coil is balanced against the external or dummy coil to obtain the greatest sensitivity. For convenience in balancing the voltages of these two coils a transformer was constructed with two windings so arranged that the currents in the two windings oppose one another. A third winding was constructed on this transformer to pick up any differences in the voltages of these two coils. The current of the third transformer winding is calibrated to measure the vibrations, in thousandths of an inch, that take place in front of the core of the test coil.

Fig. 1 shows a graphic representation of the currents in the differential three-winding transformer. When the circuit is balanced the primary currents I_2 and I_3 are equal and 180 electrical degrees out of phase. This produces zero flux in the transformer core. If the air-gap in front of one of the coils is changed, it will unbalance the circuits: I_2 will differ from I_3 as shown in the figure and a flux will be set up in the differential transformer core. The flux in the differential transformer core will generate a voltage in the secondary winding No. 1 of the differential transformer, and produce current I_1 in the oscillograph vibrator circuit. The unbalanced currents may not be exactly 180 electrical degrees out of phase with one another, as shown in the figure, as most of the unbalanced condition is due to the change in the inductive reactance of the circuit. This phase variation does not cause errors, as the same variation occurs during calibration.

In each branch of the vibration-recorder circuit there is a variable inductor, a three-dial resistor with steps of 0.1, 1.0 and 10.0 ohms respectively, a coil and a winding of a transformer, all connected in series. The two branches of the electric micrometer circuit are exact duplicates. The connections are shown in the wiring diagram, Fig. 2. Resistances R_1 and R_2 and inductances L_1 and L_2 are secondary parts of the circuit. Their function is to keep the resistance components and the inductive components of the two arms of the electric micrometer exactly equal so that the currents in each half of the circuit will have the same magnitude and the same phase displacement from the impressed e. m. f.

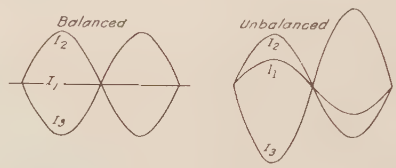

Fig. 1—Graphic Representation of the 500-Cycle Currents in the Differential Three Winding Transformer

Applications. Vibrations as small as five or ten thousandths of an inch have been measured on the periphery of a turbine wheel rotating at 1800 rev. per min. in a steel casing. This was done with the coils exposed to the steam heat and the moisture of the turbine. The whipping of rotating shafts has also been measured. The two above applications were made with an open type coil holder (without a magnetic diaphragm.) Transient oil pressure due to an explosion produced by opening a high-voltage switch in a sealed vessel have been measured with a magnetic diaphragm type of coil holder.

Investigations of the mechanical motions in various kinds of apparatus require changes in the size of the coils and the design of the coil holders. In the majority of investigations coils one inch in diameter by three-quarters of an inch deep have been found satisfactory. The number of turns required varies widely from 500 to 1500. An iron core one-half of an inch in diameter is generally used. The two coil holders in all cases should be built exactly alike so that the dummy coil and the test

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Complete copies containing Bibliography here omitted are available upon application.

coil will have the same magnetic characteristics and the same eddy-current. This will give a rough balance when the air-gaps of the two coils are the same.

A magnetic diaphragm is required in front of the test coil and dummy coil when transient pressures of gases or liquids are being investigated. The diaphragm must be suitably built as a part of the coil holder. In a case where a direct mechanical vibration is produced in a piece of apparatus the coil does not require a diaphragm in front of it. The front of the coil

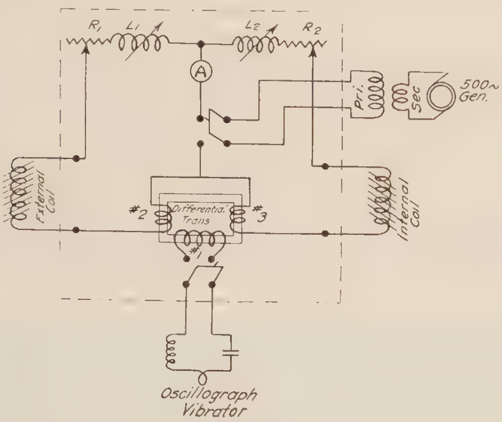

FIG. 2—CONNECTION DIAGRAM FOR THE VIBRATION RECORDER

is placed directly opposite a magnetic piece of material which may or may not be a part of the apparatus being tested. The coil is placed so that there is an air-gap between it and the piece of magnetic material in front of it. Any changes in distance between the magnetic material and the coil can be measured by the change in strength of the magnetic field at various air-gaps.

Sensitivity. Changes in the air gap between the core and the magnetic material of one-thousandth of an inch will produce a deflection on the oscillograph vibrator of from two to five millimeters. The amplitude of the vibration of the apparatus under test is magnified on the oscillograph vibrator 150 times. This magnification ratio is shown in Table I which gives the calibration of the vibration recorder. A magnification of 106 is obtained for small variations in the air-gap, but for larger variations, the magnification is 201.

Accuracy. The vibration recorder will measure accurately any small mechanical movements transient in nature, produced in a piece of apparatus. If this movement is 0.005 in. or greater, an accuracy of five per cent can be obtained.

INSTRUMENT DESCRIPTION AND CONNECTIONS TO AUXILIARY APPARATUS

Fig. 3 shows the vibration recorder as it is developed in instrument form. The two halves of the instrument are practically identical. It is approximately 25 in. long, 18 in. wide and 8 in. high. The ammeter shown in the middle is a standard G. E. type P3. The vibration recorder itself is portable although the oscillograph equipment including the 500-cycle generator is usually not constructed with this point in view.

A one-kw., 500-cycle, 110-volt generator is connected externally through a transformer to the upper left hand terminals marked "500-cycle generator." The oscillograph vibrator circuit is also connected externally to the upper right hand terminals marked "Oscillograph Vibrator." In series with the vibrator in this circuit is an inductance coil and a condenser which is set in dull resonance for 500 cycles. Tuning the oscillograph vibrator circuit accomplishes two results; it reduces the impedance to approximately four ohms effective resistance and likewise keeps down all the harmonics in the 500-cycle wave.

Before the oscillograph vibrator circuit is tuned it is very difficult to produce a balanced condition on account of the harmonics interfering. When it is tuned the harmonics disappear and the circuit can easily be balanced so that the zero line on the oscillograph including all the residual deflection is not more than two millimeters wide. The circuit is balanced roughly by setting the air-gap of the external coil approximately the same as that of the internal coil. A fine balance is obtained by moving the dial resistors and the dial inductors until a satisfactory balance is obtained as indicated on the oscillograph vibrator.

CALIBRATION

The internal or test coil is used to obtain a voltage variation due to the vibration to be measured. The external coil is a dummy coil and its function in the circuit is to furnish a voltage to balance the voltage of the internal coil. The voltage of the external coil is of a specified value assumed as a zero from which to measure the amplitude of vibration.

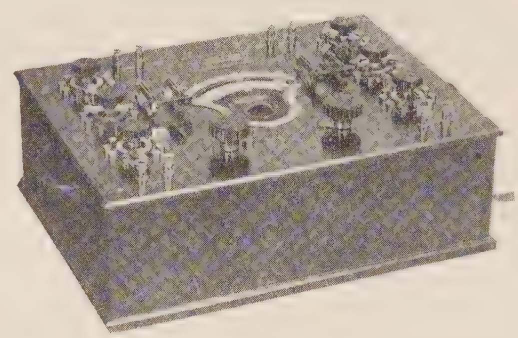

FIG. 3—THE VIBRATION RECORDER
Used to measure transient pressures and mechanical vibrations

When a calibration is started the air-gap in front of the external coil must be set approximately the same as that of the internal coil. The air-gap of the external coil is very seldom changed during the test after the balance is once obtained. The apparatus under test furnishes the internal coil with a varying air-gap corresponding to the vibration that we wish to measure. The variations in the air-gap will be recorded by de-

flections shown on the ground glass of the oscillograph, as illustrated on the calibration curves shown in Figs. 4 and 5. Curves were taken by varying the air-gap of the internal coil while holding constant that of the external coil.

Fig. 4 shows calibration curves for the internal coil for four air-gap settings of the external coil. The air-gap settings should be chosen to correspond with the nature of the test. In order to obtain calibration curve marked "50 mils" the external coil was kept at this constant air-gap and the air-gap of the internal coil was changed. Readings were taken on the oscillograph of the width in millimeters of the bright band produced by the 500-cycle wave and measurements were taken with a suitable thickness gage, in thousandths of an inch, of the corresponding air-gap in front of the internal coil. In adjusting this air-gap either the internal coil or the piece of apparatus under test may be moved.

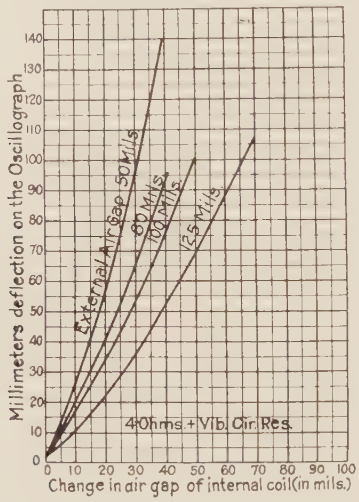

Fig. 4—Calibration Curves for the Vibration-Recorder Circuit

Showing the effects of various air-gaps between the test coil and the piece of apparatus being investigated

The sensitivity of the instrument is best, for changes of five or ten-thousandths of an inch, when the width of the bright band during calibration at the smaller lengths of air-gap of the internal coil is greater than the width of the scale of the oscillograph. The total width that can be measured on the ground glass with the zero in the center of the oscillograph scale is approximately 100 mm. For deflections greater than 100 mm., the oscillograph zero is transferred to one side of the scale and the measurement is made from zero to the maximum deflection. In this case the value obtained by measurement is doubled in order to put the results on the same basis as the smaller deflections obtained with the zero in the center of the scale. The upper points of the curves and the tabulations are made on the basis of the full (or "double") deflection.

Fig. 5 shows the deflection obtained on the oscillograph vibrator using different resistances in series with

TABLE I

Calibration of Vibration Recorder for .050 in.
(This data is not plotted on a curve)

Mils or thousandths of an inch external coil	Mils or thousandths of an inch internal coil	Millimeters deflection on the oscillograph ground glass or film	Magnification ratio
0.050 in.	0.050 in.	2. mm.	....
0.050 in.	0.040 in.	29. mm.	106.
0.050 in.	0.030 in.	61. mm.	126.
0.050 in.	0.020 in.	102. mm.	161.
0.050 in.	0.010 in.	149. mm.	185.
0.050 in.	0.000 in.	200. mm.	201.

the vibrator. These curves are shown to bring out the importance of reducing the impedance of the oscillograph vibrator circuit to a minimum by the use of the 500-cycle dull resonant vibrator circuit.

The curve marked "Decreasing Air-gap 4 ohms," was taken by setting the air-gap of both coils at 100-thousandths of an inch and decreasing the air-gap of the internal coil by successive steps. From the increasing curve and the decreasing curve it can be seen that the circuit is unbalanced when the air-gap is changed either way from 100-thousandths of an inch.

Stability of the Circuit

The stability of the electric micrometer is good because the calibration is not affected by slight voltage and frequency fluctuations of the 500-cycle generator. Changes in frequency of ± 50 cycles will affect the

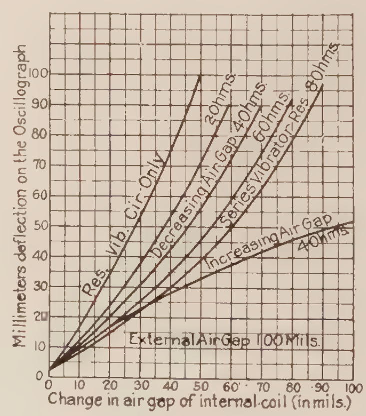

Fig. 5—Calibration Curves for the Vibrator-Recorder Circuit

Showing the effects of changing the resistance in the oscillograph vibrator circuit

calibration as the iron losses change and the oscillograph vibrator circuit will not be in resonance.

The stability of the circuit is not disturbed seriously due to the internal coil heating up more than the external coil as this uneven heating can be compensated for by changing R_1 and R_2 at any time during the test. Adding 20 ohms to R_1 and 20 ohms to R_2 will not change the original calibration. The best results are obtained if the electric micrometer circuit and the oscillograph galvanometer field are allowed to heat up about one-half of an hour before using.

Tests Results Shown on Oscillograms

Fig. 6 shows a decaying mechanical oscillation of 36 cycles per second which was taken for illustrative purposes only. This oscillation was produced by a vibrating reed clamped to an iron support. Position marked *A* shows the reed pulled over and held 0.044 in. from rest towards the internal or test coil. The reed was first set at 0.125 in. in its rest position. The calibration curve for this film is shown on Fig. 4. Position *B* shows the first cycle after the reed was released and allowed to swing free. The first swing did not return entirely to its original position of 0.044 in. and it, therefore, returned to a position of 0.039 in. representing a total swing of 0.078 in. Position *E* likewise represents a mechanical deflection of 0.036 in. one-half amplitude of the reed. Position *F* represents 0.023 in. one-half amplitude and it is the 12th swing of the reed towards the internal coil which occurred approximately one-third of a second after the reed was released.

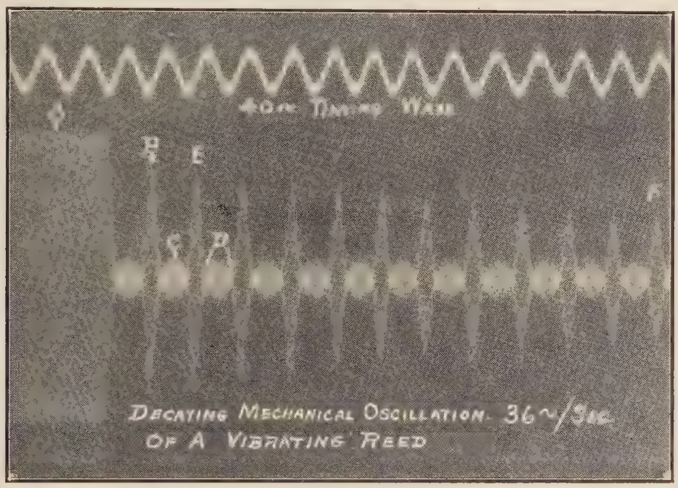

Fig. 6—Oscillogram Showing a Simple Mechanical Oscillation Produced by a Vibrating Reed

Position *B* represents the reed at its nearest position to the internal coil after release and position *C* represents the reed at its greatest distance away from the internal coil in the cycle of which *B* is the beginning. Position *D* represents the reed passing through its rest position or the balanced positions for the electric micrometer circuit. Any simple natural vibrating mass passes through its rest position twice in making a complete cycle.

Fig. 7 is a record of a vibration of an eight-foot diameter turbine wheel rotating 1280 rev. per min. and vibrating 0.024 in. in six segments or nodes around the periphery. The internal or test coil was held in a bracket fastened to a stiff wheel which rotated at the same speed and on the same shaft as the wheel under test. (See Fig. 8) The stiff wheel ran rigidly at all speeds for which wheels are ordinarily tested and had known vibration characteristics at speeds much higher than that of the wheel being tested. Positions marked with an arrow show every revolution of the wheel. In one revolution there are six different positions shown. These correspond to segments between the six nodes or rest positions of the vibrating wheel. Positions 1, 3, and 5 represent negative segments, or wheel displacements from rest, away from the internal coil. Positions 2, 4 and 6 represent positive segments, or vibration from rest, towards the internal coil.

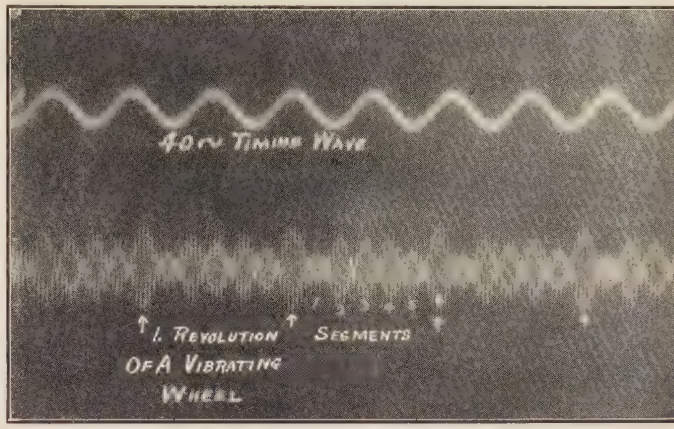

Fig. 7—A Record of a Vibration of an 8-Ft. Diameter Turbine Wheel

Rotating 1280 rev. per min. and vibrating 0.024 in. in six segments around the periphery

The deflections under the arrows are larger than the other five intermediate deflections: The reason for this is that the turbine wheel received a slight end thrust or quiver every revolution. This is likewise shown in producing a smaller deflection next to the largest deflection. This quiver in the wheel for every revolution represents approximately two-thousandths of an inch variation. These total deflections are actual measurements of mechanical movements of 0.012 in.

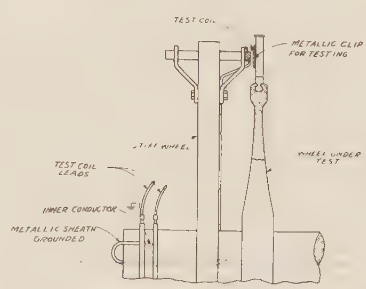

Fig. 8—Arrangement of Test Coil and Holder for Vibration Measurements on a Turbine Wheel

or one-half the total amplitude of the vibration of the wheel. The total amplitude of the vibration of the wheel is 0.024 in. The reason this deflection, shown on the oscillogram Fig. 7, represents one-half the total amplitude of the vibration is that the calibration was taken while the wheel was moved from rest towards the coil. Deflections away from rest do not require a calibration. The mechanical deflections of the wheel on both sides of the rest position are the same.

Abridgment of

The Mechanism of Breakdown of Dielectrics

BY P. L. HOOVER[1]

Associate, A. I. E. E.

Synopsis.—*In attempting to analyze various experimental data that have been obtained in researches on dielectric phenomena in high-voltage cable insulation and other dielectrics, the various existing theories of dielectric behavior have seemed inadequate. A critical study has therefore been made of these theories in an attempt to obtain a working hypothesis that more nearly meets the stringent requirements of experimental facts.*

The logarithmic formula is shown to give erroneous results if applied to high-voltage cables when they are operating under high stress. The gradient in a cable must be calculated from the volt-ampere characteristic of the dielectric when stresses above the elastic limit are used. For stresses below the elastic limit it makes no difference which method is used, but at high stresses an entirely different gradient distribution is obtained when calculated from the volt-ampere characteristic.

Likewise, when an insulation is operated above the elastic limit the stress ceases to be a critical factor, but the strain is of utmost importance. In comparing cables that are operating under high voltages, therefore, the strain at the core should be considered rather than the stress at the core. Stress is given by the voltage gradient and strain by the polarization or the current density in the dielectric.

Since there is always a conduction current flowing, there must be mobile or free ions present. It is assumed that these free ions or electrons come from the molecules of the dielectric and that the number that are present depends on a condition of equilibrium existing between the molecules and the free ions. There exists then a state of kinetic equilibrium between the molecules and the free or mobile ions. Any change in external or internal conditions will disturb the equilibrium and thus change the electrical behavior of the dielectric. Thermal effects and corona effects are accounted for on this basis.

Breakdown occurs when the equilibrium conditions are so disturbed that the insulation as a whole becomes unstable, electrically. High stress or strain and high temperature affect the conditions of equilibrium decidedly.

Corona in gases, oils, and solids consists of minute disruptive discharges that are initiated by rapid changes in equilibrium conditions when the dielectric is overstressed. In solids, however, where the ion mobility is very low and the ion friction high, there will not in general be a corona effect observed because there can be no rapid readjustment of equilibrium conditions. If the insulation is not homogeneous, or if it is composite, there will likely be internal discharges, a corona effect, when the weaker dielectric is overstressed. Moreover, since the molecules of a solid can not readjust themselves quickly to the new conditions of equilibrium imposed by a high voltage suddenly applied, there will be high local stresses and strains set up which may result in mechanical deterioration of the dielectric, that is, chipping or cracking of the dielectric.

Breakdown, therefore, will take place when the insulation is rendered unstable by disturbing the equilibrium conditions, regardless of whether it is due to mechanical strains, electrical strains, or to thermal effects. The tri-fold nature of the phenomenon must be considered in the complete analysis of the problem.

Introduction

The mechanism of breakdown of dielectrics is of the highest importance and yet at the present time it is very little understood. It is the purpose of this paper to discuss and to extend some of the theories of breakdown which have been presented heretofore.

The mechanism of breakdown of single-conductor cables has a particular interest, since the geometry is comparatively simple and it is possible to overstress parts of the insulation without complete rupture taking place. That is, if the gradient is calculated by means of the well-known logarithmic formula for a cable with a ratio of outer to inner radius greater than the Naperian base e and for a voltage near the breakdown value, it is found that the inner layers of insulation are operating at gradients considerably higher than any that the insulation would stand if it were made up in flat sheets. This same effect is brought about whenever a dielectric is in a non-uniform field, although, in general, it is not possible to derive a simple mathematical formula for the gradient distribution of a complex field.

There is, however, considerable justification for skepticism regarding the possibility of overstressed insulation, that is, regarding the validity of the logarithmic formula when used for calculating gradients when the insulation is stressed beyond the elastic limit. In using the logarithmic formula for calculating gradients, it is tacitly assumed that the dielectric has the same electrical constants at and beyond breakdown that it has at low gradients. Reasoning by analogy from other physical phenomena, we should not expect this to be the case; in fact, we would expect new laws to enter as soon as the elastic limit of the material is exceeded. For example, Hooke's law is used in determining the stress distribution in beams and supports of all kinds as long as the elastic limit is not exceeded but beyond the elastic limit Hooke's law does not hold and cannot be used.

Historical Review

To account for these phenomena of overstressed insulation, various theories have been proposed, such as the maximum stress theory, the average stress theory, Fernie's[2] minimum stress theory, Russell's[3] theory, and Osborne's[4] theory. These theories, and in partic-

1. Research Fellow, The Harvard Engineering School.

Presented at the Annual Convention of the A. I. E. E., at White Sulphur Springs, W. Va., June 21-25, 1926. Complete copies available upon request.

2. F. Fernie, Insulating Materials, *Beama*, 1920, p. 244.

3. A. Russell, *Dielectric Strength of Insulating Materials and the Gradient of Cables*, Journal of A. I. E. E., Vol. 40, p. 6, 1907.

4. H. S. Osborne, *Potential Stresses in Dielectrics*, Journal of the A. I. E. E., Vol. 29, p. 1553, 1910.

ular the minimum stress theory, have been discussed at length by Simons[5] and will not be considered in detail in this paper.

Differing substantially from these theories just mentioned is the pyroelectric or thermal theory of breakdown as developed by Wagner[6] and by Hayden and Steinmetz.[7]

The pyroelectric theory assumes that solid insulators have volt-ampere characteristics similar to those shown in Fig. 1, and that this type of characteristic is due solely to the high negative temperature coefficient of resistance of the material.

The question arises, however, as to whether or not this type of volt-ampere characteristic is entirely the result of a high negative temperature coefficient of resistance. Might it not be due, at least in part, to change in resistivity with current density due to some molecular phenomenon? In any case, breakdown will occur when $d E/d I = O$, for at this point the current will increase to the short-circuit value of the supply.

Günther-Schulze[8] has made a study of the phenomena of dielectric breakdown and states that different definitions of dielectric strength may be given according to the way in which the problem is approached. To quote from his paper:

"Accordingly, the dielectric strength is the lowest potential gradient at which the current through the dielectric is replaced by an independent discharge which is self-increasing. (a spark)." (*Translated*) This gives what Günther-Schulze calls the dielectric impact strength (Stossfestigkeit).

As a second point of view, he gives the following: "These considerations result in the following definition of the dielectric strength: the dielectric strength of a dielectric is the lowest potential gradient at which the bonds between the charges in a dielectric are severed so that a discharge passes through the dielectric." (*Translated*) This he calls the dielectric tensile strength (Reissfestigkeit).

Günther-Schulze then considers various data and concludes or assumes that breakdown in liquids is really a gas discharge in disguise. He states:

"Thus, if an increasing field is applied to the liquid dielectric, the velocity of the ions in the field will increase. But this again means an increased ion friction and an increased heating of those parts of the dielectric that surround the path of the ion. If the increasing field is continued, the heating finally becomes so great that the ions leave an extremely minute, sub-microscopic vapor track in the dielectric. If an ion comes into this vapor track, it is capable of producing new ions through collision, thus initiating the spark discharge, provided the potential drop along the path of the ion is sufficiently high." (*Translated*)

For solid dielectrics he states that the phenomena are somewhat similar. The extremely high ionic friction causes heating effects that result eventually in breakdown. It is, then, the dielectric impact strength that determines the stability of the insulation, the dielectric tensile strength playing a relatively insignificant part in breakdown phenomena.

Thus, dielectric breakdown, according to Günther-Schulze, is a pyroelectric effect. The concept of dielectric impact strength, as he describes it, is only a physical picture, in terms of ions and atoms, of the pyroelectric theory of breakdown.

The concept of dielectric tensile strength, however, should not be thrown aside so hastily. A further consideration of essentially this same idea, but modified considerably and from a different point of view, leads to some very interesting conclusions and results.

Theoretical Considerations

As was first pointed out by Maxwell, the total current in a dielectric consists of the polarization current and the conduction current, the two currents being super-imposed. Is it not possible that there is some relation between them since they are contemporaneous phenomena?

At low gradients there is always a current flowing and this current is due to moving ions or electrons. There is also a certain polarization of the dielectric. At higher gradients the polarization increases and so does the conduction current. That is, the number of mobile charges increases with the degree of polarization of the dielectric. This suggests that the mobile ions must come from the molecules of the dielectric. If this is the case, there must exist a state of equilibrium, a kinetic equilibrium, between the mobile or free ions and the molecules of the dielectric. Increasing voltage gradient would increase the polarization and establish new conditions of equilibrium, the tendency being to increase the number of free ions and thus increase the conductivity of the dielectric. Ultimately a gradient will be reached where the number of ions required to establish the equilibrium will be so great that the molecular bonds will be destroyed and dynamic rupture of the insulation will take place.

The idea of assuming molecular dissociation at comparatively low-voltage gradients may seem rather bold at first sight, but a little thought will show that it does not demand any radical departure from the already well established theories of molecular behavior. In the first place, with liquids, and especially with solids, the inter-molecular fields are quite as important as the intra-molecular fields. The great tensile strength

5. D. M. Simons, *On the Minimum Stress Theory of Cable Breakdowns*, Journal of the A. I. E. E., Vol. 41, p. 557, 1922.

6. K. W. Wagner, *The Physical Nature of the Electrical Breakdown of Solid Dielectrics*, Journal of the A. I. E. E., Vol. 41, p. 288, 1922.

7. J. L. R. Hayden and C. P. Steinmetz, Insulation Failure—A Pyroelectric Effect, *Electrical World*, October 1922, p. 865.

8. A. Günther-Schulze, The Dielectric Strength of Liquids and Solids, *Jahrbuch der Radioaktivität und Elektronik, 1922*, Vol. 19, p. 92.

of solids can only be explained on the basis of strong inter-molecular fields. Any change in the molecular structure of a solid produces corresponding changes in all of its physical properties due to the changes in the inter-molecular fields. Consequently it must be assumed that, in solids at least, the electrons in the atom are influenced not only by their own nuclei but also by the fields of the neighboring atoms or molecules. Under such conditions it is probable that the atoms can be ionized; that is, an electron can be removed with much weaker external fields than would be necessary if the atom were isolated in space.

Furthermore, molecular theory demands that the molecules be in motion except at absolute zero, so that any theory dealing with molecular behavior must necessarily be a kinetic theory. With these ideas in mind, it is easy to picture an electron in a dielectric moving about with its nucleus, but also under the influence of the strong inter-molecular fields.

For low gradients, the number of ions drifting, that is the magnitude of the conduction current, will be proportional to the gradient. At higher gradients, as the polarization of the molecules increases, the molecular bonds will become weaker and weaker and the number of electrons which are drifting will increase more rapidly than the gradient increases, and there will be an increase in the conductivity of the dielectric. At some critical gradient the molecular bonds will be entirely broken and dynamic rupture will take place. The phenomenon throughout is essentially that of a kinetic equilibrium between the free or drifting electrons and ions and the polarized molecules of the dielectric.

On the basis of these ideas, the volt-ampere characteristic would have the form of the curves of Fig. 1. Curve A is from some experimental data of Wagner[9] on oiled paper, while Curve B is an empirical curve made to fit Curve A as nearly as possible in order that some numerical computations could be made. The equation of Curve B is

$$e = \frac{175\, i}{1 + 0.1\, i^2} \tag{1}$$

where e is kv. per cm.
and i is milliamperes per sq. cm.

Referring to Curve B of Fig. 1, it is seen that at low-current densities, *i. e.*, when $0.1\, i^2$ is negligible in comparison to unity, the current is proportional to the voltage. At higher current densities, the current increases faster than the voltage and the curve takes the form shown. The equilibrium conditions are perfectly stable up to the maximum point of the characteristic, at which point rupture occurs. If some means be taken to prevent an excessive current, however, it is possible to maintain stable equilibrium in the dielectric even though it be operated beyond the maximum point of the volt-ampere characteristic. By using a high-resistance, mosaic electrode, Wagner was able to determine experimentally the Curve A of Fig. 1.

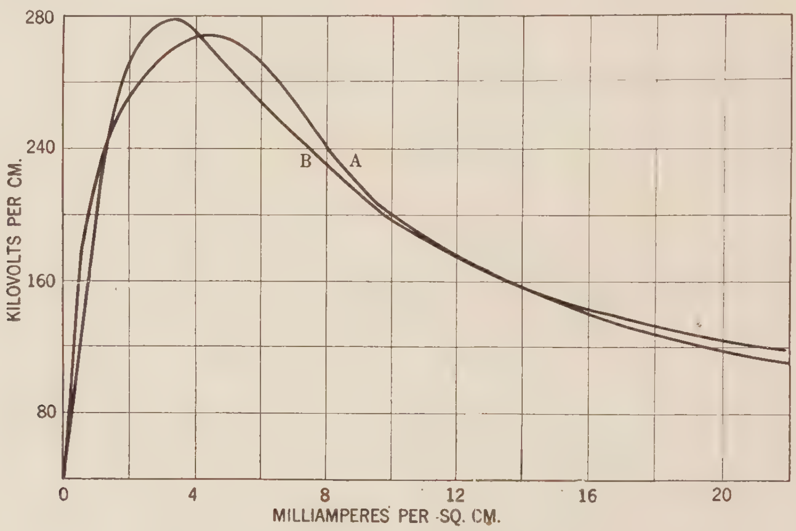

Fig. 1—Volt-Ampere Characteristics

A. From data of Wagner (Oiled Paper)

B. $e = \dfrac{175\, i}{1 - 0.1\, i^2}$

Cable Breakdown

If a cable is constructed of an insulating material having a volt-ampere characteristic similar to those of Fig. 1, it follows that at low current densities the current will be proportional to the voltage. At higher current densities and voltages, when the inner layers begin to be overstressed, the current through these layers will begin to increase more rapidly than the voltage across

9. K. W. Wagner, Loc. Cit. See also Electric Cables, by W. A. Del Mar, p. 79.

these layers. Ultimately, the inner layers will be operating at a point beyond the maximum of the volt-ampere characteristic, but the outer layers, not being overstressed, will prevent complete rupture of the cable.

The possibility of such an analysis by means of the volt-ampere characteristic was recognized and suggested by Peaslee.[10] It is the purpose of the remainder of this paper to carry the analysis still further and to compare the results with certain experimental data.

In the appendix of the complete paper it is shown that the voltage across a cable made from a material with a volt-ampere characteristic given by equation (**1**), Curve *B* of Fig. 1, will be

$$E = \frac{175\, I}{4\,\pi} \operatorname{Log}\left(\frac{0.1\, I^2 + 4\,\pi^2 R^2}{0.1\, I^2 + 4\,\pi^2 r^2}\right) \qquad (\mathbf{2})$$

Where

E = Total voltage in kv.
I = Milliamperes per cm. length of cable
R = Outer or sheath radius (cm.)
r = Inner or conductor radius (cm.)

$$\operatorname{Log}\left(\frac{0.1\, I^2 + 4\,\pi^2 R^2}{0.1\, I^2 + 4\,\pi^2 r^2}\right) = \frac{0.8\,\pi^2 I^2 (R^2 - r^2)}{(0.1\, I^2 + 4\,\pi^2 R^2)\;(0.1\, I^2 + 4\,\pi^2 r^2)} \qquad (3)$$

From equations (**2**) and (**3**), the puncture voltage of the various cables can be calculated. Fig. 3 shows curves of puncture voltage plotted as a function of the ration r/R and obtained in this way. Curve *A* is for cables with a constant-conductor radius of 0.158 cm.; Curve *B* is for cables with a constant sheath radius of 5.03 cm.; and Curve *C* is for cables with a constant insulation thickness of one cm.

In Fig. 4 are curves plotted from data obtained experimentally by various observers. Curves *A* and *B* resemble the A and *B* curves of Fig. 3. Curves *B′* and *B″* resemble *B* of Fig. 3, except for the tendency to droop at small values of r/R. The five points in the center of the plot, numbered 1, 2, 3, 4, and 5, are from data by Fernie and correspond to a constant insulation thickness. The points are so erratic in their positions that no representative curve can be drawn.

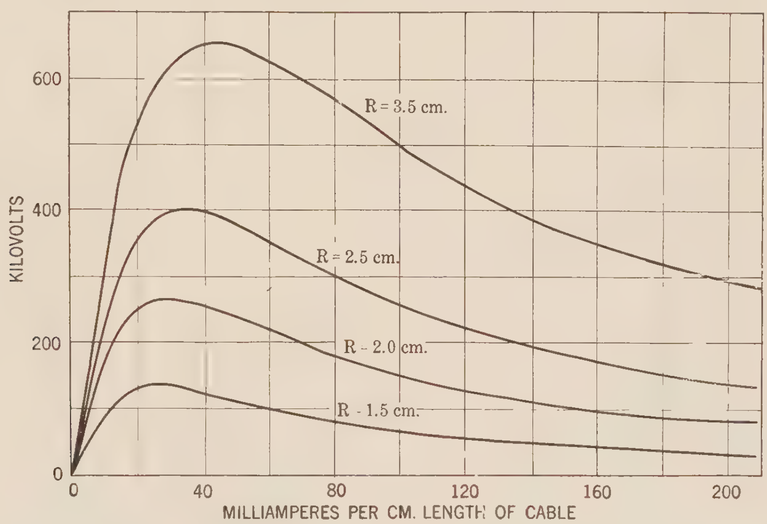

FIG. 2—VOLT-AMPERE CHARACTERISTICS FOR CABLES
Inner radius 1 cm.

From equation (**2**), the volt-ampere characteristics of cables of this material can be plotted. Fig. 2 gives the volt-ampere characteristics for cables of inner radius of one cm. and with various outer radii. These characteristics have the same general shape as those of Fig. 1. This, of course, is to be expected, and it is seen that the cable insulation as a whole increases in conductivity as the current increases. The insulation, however, remains stable regardless of the stress relations in the inner layers until the maximum point of the particular cable characteristic is reached. This point can be found by setting the derivative of equation (**2**) equal to zero, or,

10. W. D. A. Peaslee, Discussion, JOURNAL of the A. I. E. E., Vol. 41, p. 620, 1922.

They indicate, however, a rough agreement with Curve *C* of Fig. 3.

These experimental checks are hardly sufficient to establish the theory as developed positively, but the agreement is certainly sufficiently good to warrant further study.

It is of interest to investigate the question of voltage gradient in various parts of the cable insulation on the basis of this theory. The gradient is given by

$$e = \frac{2\,\pi\, 175\, r\, I}{4\,\pi^2 r^2 + 0.1\, I^2} \qquad (4)$$

(See appendix of complete paper.)

Fig. 5 gives the gradients in kv. per cm. at various distances from the axis for two cables, when the im-

pressed voltage is equal to the breakdown voltage. It is seen that the maximum gradient is at some point near the center of the wall of insulation and is not at the surface of the conductor, as is ordinarily assumed. In fact, the gradient at the conductor is less than that at any other point in the insulation.

To emphasize this point and to show the change in gradient distribution with increasing voltage, the curves of Fig. 6 are given. It is seen that, for low voltages, the maximum gradient is located at the core and that the gradient practically follows the logarithmic law. At higher voltages, and hence higher current densities, the gradient departs from the logarithmic law and has the form shown by the curves. It is seen that the gradient never exceeds a certain definite maximum. This maximum value is determined by the volt-ampere characteristic, Fig. 1, and for the case illustrated is 178 kv. per cm. The position of this point of maximum gradient moves gradually from the surface of the conductor towards the sheath, but puncture occurs before the sheath is reached.

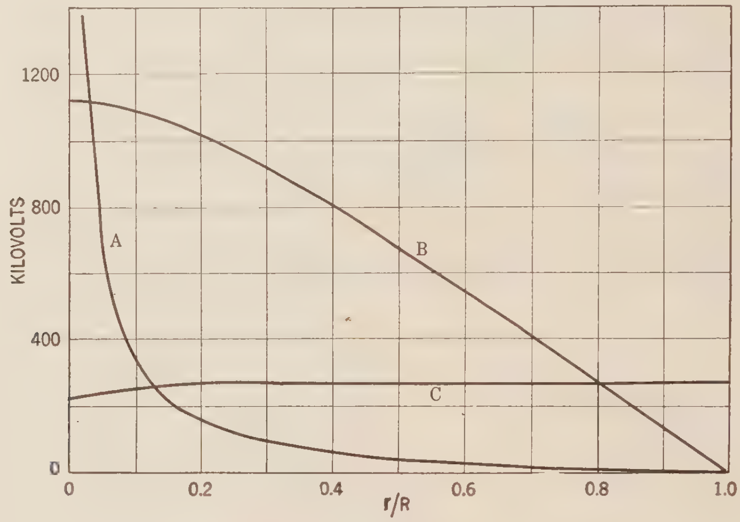

Fig. 3—Puncture Voltage of Single-Conductor Cable vs. r/R

A. r = Constant
B. R = Constant
C. $R - r$ = Constant

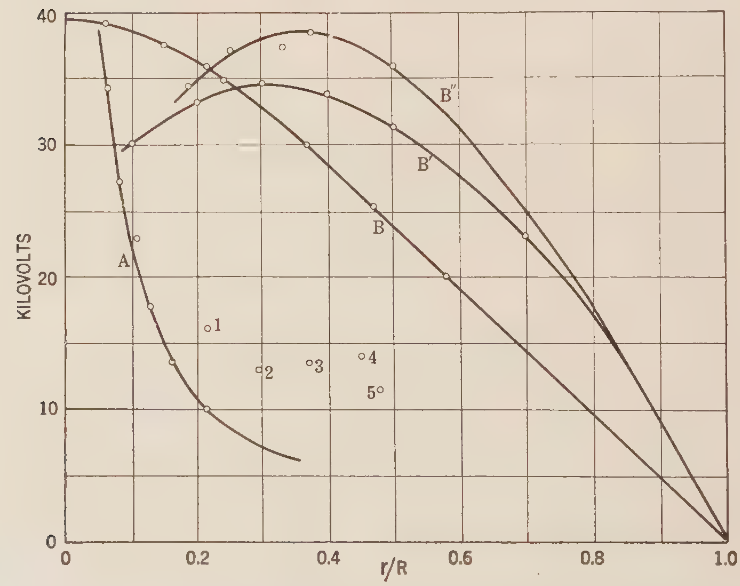

Fig. 4—Puncture Voltage vs. r/R

A, B and B' from Middleton, Dawes and Davis; B'' from Wiseman. Points 1, 2, 3, 4, and 5 from Fernie. (Multiply ordinates by 10 for Fernie's data.)

It is important at this time to investigate the stress-strain relations in the dielectric. It seems evident that stress is given by the voltage gradient and strain by the polarization or probably by the current density. We have then the stress proportional to the strain for low stresses, but for higher stresses the strain increases faster than the stress. Finally, the ultimate strength is

exceeded and the strain increases indefinitely even with a decrease in stress. The analogy with the stress-strain relations of mechanics is obvious, the only difference being that the elastic limit and the ultimate strength in dielectrics are probably not as definite as they are in mechanics.

The elastic limit may therefore be defined as in mechanics as that stress at which the stress-strain diagram begins to deviate from a straight line, the ultimate strength likewise being defined as the stress at the maximum point of the stress-strain diagram. The stress-strain diagram of a dielectric is its volt-ampere characteristic.

From the foregoing it appears that in cables operating

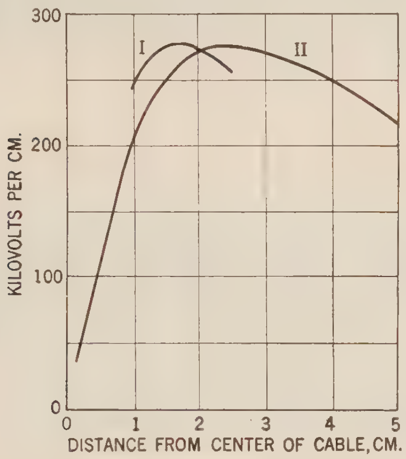

FIG. 5—GRADIENT DISTRIBUTION IN SINGLE-CONDUCTOR CABLES AT THE BREAKDOWN VOLTAGE

I r = 1.0 cm.
R = 2.5 cm.
II r = 0.16 cm.
R = 5.03 cm.

at high stresses, the logarithmic formula fails completely to give the correct gradient distribution. Furthermore, it seems that stress or voltage gradient is not the best criterion to use in judging the quality of various insulations when they are operating beyond the elastic limit. Strain is obviously the factor that is of utmost importance when once the elastic limit is passed. Consequently, in comparing various cable insulations, the strain at the core should be used rather than the stress at the core, the strain being given by the current density. This concept is thought to be very important.

There is, however, when alternating currents are used, some question as to whether the total current or simply the in-phase current should be used to determine the strain. The polarization of the dielectric determines the quadrature current and the conductivity and energy loss determine the in-phase current. So long as both of these two components increase uniformly with the stress, the total current will increase uniformly with stress. As soon as one of the components begins to deviate from a linear relation, however, the total current will correspondingly deviate from a linear relation with stress. Furthermore, if a stress is reached where either component of the current increases indefinitely with no further increase of stress, then the total current must likewise increase indefinitely. Consequently it seems immaterial whether the total current or simply the in-phase current is used in determining the strain in the dielectric and it is not evident at this time which of the two will give the best indication of the true strain in the dielectric.

The one outstanding effect that has not been explained is the drooping of the curves B' and B'' in Fig. 4. In these two cases, the sheath radius was kept constant and the conductor was made of smaller and smaller radius. There seems to be a point where further decrease of conductor radius not only fails to increase the puncture voltage but actually diminishes it. It hardly seems possible that an increase in insulation thickness should decrease the breakdown voltage, but such seems to be the case so far as these particular data are concerned.

Osborne's[11] theory explains this effect by assuming ". . . that a solid dielectric, when overstressed, is not disrupted uniformly, but that the material is affected as though it had been pricked by a number of needlepoints."

The ends of these needlepoint ruptures then become points of very high stress and therefore cause rupture of the entire dielectric. Considerable evidence exists supporting the needlepoint theory but little is known as to the origin, nature, and effects of these needlepoint ruptures. Their general character would suggest a high frequency discharge and this suggestion seems to be borne out by further analysis.

Much has been written on corona in oils and in

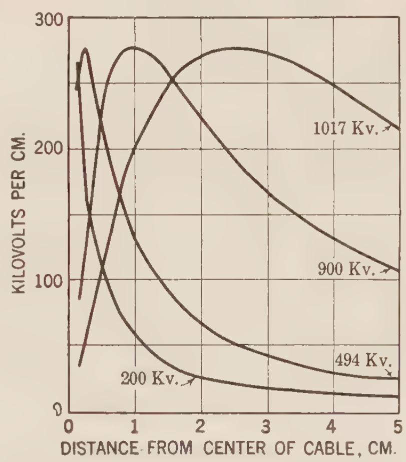

FIG. 6—GRADIENT DISTRIBUTION IN SINGLE-CONDUCTOR CABLE

Breakdown voltage = 1017 kv.
r = 0.16 cm. R = 5.03 cm.

solids, but there is still cause for considerable speculation as to the fundamental nature of the phenomenon. It probably is a high-frequency rupture. An experimental arrangement designed to show the nature and effects of corona in oils is illustrated in Fig. 7. Voltage was applied between the brass rod and the

11. H. S. Osborne, Loc. Cit., p. 1577.

water sheath. At about 20 kv., numerous discharges took place between the brass rod and the inside of the glass tube A. The apparatus, being transparent, afforded opportunity for visual observations. It was noticed that the discharges resembled ordinary spark discharges except that near the interface between the oil and the glass the spark discharge, or corona, spread out over considerable area; that is, the spark is not strictly radial but seems to consist of streamers that spread throughout an appreciable volume of the oil. Although corona in oil thus consists of disruptive discharges, there is some question as to their needle-like character. In fact, it seems as if these discharges are propagated outward and get thinner and thinner as they go. A somewhat analogous case would be a lightning bolt discharging a cloud by numerous streamers extending throughout the volume of the cloud but uniting to form a single bolt to earth.

The mechanism of these corona discharges in oil is readily understood when we recall the physical picture

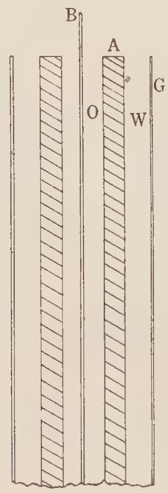

Fig. 7—A, Glass Tube; B, Brass Rod; C, Transformer Oil; W, Water Electrode; G, Glass Tube

of a kinetic equilibrium between the mobile ions and the molecules when the oil is under electric stress. If the oil is under high stress, near or beyond the breakdown point, there will be a comparatively great number of ions free to move, for the molecular bonds will be practically broken. Ions of one polarity will tend to move toward the outer electrode and those of the opposite polarity will move toward the inner electrode. The glass tube prevents any concentration of the ions that are moving toward the outer electrode but from the inner electrode sparks or corona discharges will radiate outward and discharge a finite volume of the ionized dielectric. Heterogeneity of the oil accounts for the concentration of the ion flow and the resulting spark discharge, rather than a more uniform corona glow.

Nevertheless, regardless of the nature of these discharges in the oil, considerable damage is done to the dielectrics. The oil is decomposed, gases being evolved quite rapidly, and the inner surface of the glass tube is badly cracked and chipped. Fig. 8 is an enlarged photograph of a glass tube after a few minutes' application of voltage. The various markings are chips and cracks along the surface of the inner bore of the tube. This tube did not puncture, although some of the cracks extend fully half-way through the wall of the tube.

This chipping and cracking of the glass tube may be due to a rather high temperature locally, or it may be

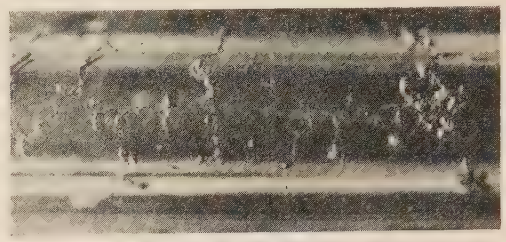

Fig. 8

due to the high-frequency character of the discharges. Peaslee[13] has obtained somewhat similar effects in porcelain. He, however, superimposed high-frequency pulses on the 60-cycle voltage and therefore knew definitely the cause of the phenomena which he observed.

In order to check up on the corona effect in solids, glass thermometer tubes were used. Mercury formed the inner electrode, which was 0.2 mm. in diameter, and water was used for the outer electrode. The ratio of R/r was 33. This tube was known to puncture between 35 and 40 kv., so that 34 kv. was applied and held for half an hour. During this interval nothing happened. There were no visual signs of stress or other effects to indicate that the tube was operating near the breakdown voltage. Due to the large ratio of R to r, the inner layers must have been strained far beyond their breakdown point.

Upon increasing the voltage gradually during 30

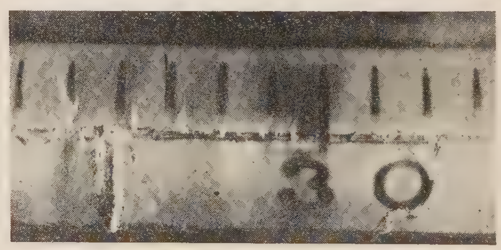

Fig. 9

seconds to 37 kv., the tube punctured. Examination showed that there were three distinct places where the tube punctured. Furthermore, throughout the length of the tube the inner wall was chipped and cracked. Figs. 9 and 10 are magnified photographs of parts of the tube. Fig. 9 shows two of the three breakdown points, one at division 26 and one at division 32. The third was at division 50. In Fig. 10 is shown a portion of the tube that was not punctured, but the chips and cracks along the inner bore of the tube are plainly

seen. This effect is undoubtedly a high-frequency phenomenon. There is some question, however, as to whether the high-frequency surges are a consequence of breakdown or are the actual cause of breakdown.

The high-frequency character of the phenomenon is suggested by the fact that several distinct ruptures were observed and also by the numerous chips and cracks along the inner bore of the tube. It is difficult to conceive of this chipping and cracking being due to a simple release of the stress but on the other hand a rapid alternation of stress would very likely result in cracking due to mechanical strains set up as a result of the rapid change in the polarization of the dielectric.

These experiments indicate that corona does not occur in solid dielectrics even when they are operated beyond the elastic limit. Thus the low mobility of the molecules and ions in the solid dielectric tends to prevent the formation of corona and likewise increases the stability of the insulation even when it is operated beyond the elastic limit. This extreme stability probably will not be found, even in solids, if there is any appreciable nonhomogeneity of the dielectric. For this reason composite or laminated insulations are particularly subject to corona phenomena, *i. e.*, internal discharges, when the weaker dielectric is over-strained. The complexities introduced by composite insulation are so numerous that they will not be discussed at this time.

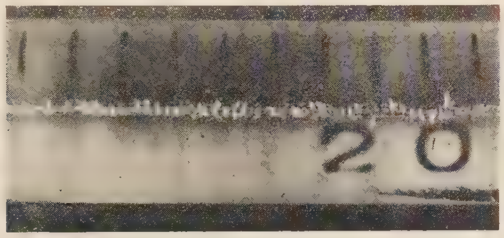

FIG. 10

The drooping of the Curves B' and B'' in Fig. 4 is explained, therefore, by assuming that the inner layer of insulation could not have been homogeneous. In both of these cases very small conductors were used, less than one mm. in diameter. With these very small conductors, it was, no doubt, impossible to get uniform vulcanization of the rubber insulation or uniform solidification of any insulating material. The resulting heterogeneity of the dielectric would cause internal discharge within the inner layers and thus the stability of the dielectric as a whole would be decreased; that is, the puncture voltage would be lower than would be the case if there were no internal discharges.

In this connection, however, it is well to mention some work by Kennelly and Wiseman[15] where they found that for varnished cambric there was a diminution of 14.8 per cent in puncture voltage when an 18.1-sq. cm. electrode was used in place of a 1.13-sq. cm. electrode. However, if sixteen of the smaller electrodes were connected together so as to have the same total area as the larger electrode and if some resistance was inserted between the different small electrodes, the puncture voltage for the combination was the same as for a single small electrode. On the other hand, if the small electrodes were connected by a low resistance as by fastening them into a brass plate, the puncture voltage was practically the same as with a single large electrode. It was suggested at the time that this effect might be due to high-frequency surges, the resistance serving to damp them out and thus give a higher puncture voltage. It would seem that in this case the high-frequency surges took place just before breakdown and were the cause of breakdown taking place at a lower voltage than otherwise would be the case.

13. W. D. A. Peaslee, *Insulation Failures under Transient Voltages*, JOURNAL of the A. I. E. E., Vol. 35, p. 1187.

15. A. E. Kennelly and R. J. Wiseman, The Apparent Dielectric Strength of Varnished Cambric, *Electrical World*, Vol. 70, p. 1138.

CONCLUSIONS

The mechanism of breakdown is not a simple phenomenon. The one fundamental concept is that in the dielectric there is a kinetic equilibrium between the mobile charges and the molecules. However, if there is any appreciable heating effect due to the conduction current or to dielectric losses, the equilibrium conditions will be changed. Therefore, in the complete analysis of the phenomena, the thermal effect must be considered. Then again, if the field is not uniform or if the dielectric is composite or heterogeneous, there is the possibility that part of the insulation will be over-strained and internal discharges are then likely to initiate high-frequency effects that disturb the stability of the dielectric as a whole. All of these three effects are undoubtedly present in every breakdown, but in many cases one or even two of them may be negligible. Experiments can be designed to show any one effect by reducing to a minimum the effects of the other two. It seems that in the past this tri-fold nature of the phenomenon has not been fully appreciated and has been the cause of much confusion. The term tri-fold may be misleading, for they are not three separate effects, but three manifestations of essentially the one phenomenon of kinetic equilibrium between the ions and the molecules of the dielectric.

The author is indebted to the members of the Electrical Engineering staff of the Harvard Engineering School, and especially to Professors H. E. Clifford and A. E. Kennelly, for suggestions in the preparation of this paper. The work has been done at the Harvard Engineering School under the auspices of the Cable Research Committee, which is a sub-committee of the appropriate committees of the National Electric Light Association, the American Institute of Electrical Engineers, and the Association of Edison Illuminating Companies.

Abridgment of

The Rectification of Alternating Currents with Steel Enclosed Mercury Arc Power Rectifiers and their Auxiliary Devices

BY OTHMAR K. MARTI*

Synopsis.—*Recently many publications have been issued on mercury arc rectifier installations in this country and in Europe, as well as on the theory of their voltage and current performances. Nevertheless, it seemed that it might be of interest to give a condensed paper dealing with the most important theoretical treatments, as well as a description of a steel enclosed rectifier of modern design.*

The fundamental theory of these rectifiers is discussed, touching only slightly upon the physical phenomena, but treating particularly of the theory involved in the practical applications. The effects of various factors on the rectifier characteristics and operation are dealt with, and the methods used for calculating the relations of voltages, currents, transformer ratings, etc., are given and tabulated. Moreover, there are mentioned the latest developments of the rectifier proper, as well as the auxiliary devices. Included in this is the design of the transformers from a mechanical point of view, making them rigid enough to stand the mechanical stresses forced upon the windings under abnormal operating conditions; and from an electrical point of view, giving the characteristics of connections such as zig-zag windings, special polyphase windings, and the introduction of reactance absorption coils in the neutral connections of the transformer. Special attention is paid also to the anodes and their cooling equipment, and to the seals, several ingenious points being brought out in their construction.

The vacuum question also is considered one of the most important, not only from the standpoint of producing and maintaining the vacuum, but also from the standpoint of measuring it. The importance of properly measuring the degree of vacuum, as well as the amount of mercury and other vapor present in the cylinder, is brought out, since it was found that the well-known devices for measuring a vacuum, such as McLeod's vacuum gage, did not give the actual conditions existent in the cylinder, but only a relative indication, namely, the pressure of the perfect gases. A new vacuum-measuring gage of novel design, which only very recently has been developed to its present state of perfection, is described in detail and its operation explained. This gage makes it possible to measure and record the absolute pressure of the gases and vapors contained in the rectifier cylinder.

The preparation of the rectifiers for service and their operation are described, and special attention is given to the numerous advantages secured by the use of rectifiers in substations. To simplify operation and to assure continuity of service, a simple and reliable method of ignition and excitation had to be developed. Without touching upon the two methods formerly employed, i. e., d-c.—a-c. ignition and excitation, a new method, lately developed, which proved to be extremely serviceable in practise, is described and illustrated in detail.

The simplicity of starting and operation, the ease of control and the adaptability to full automatic operation, as well as the high efficiencies of these rectifiers, are dealt with and all the advantages are recapitulated at the end. A somewhat exhaustive bibliography, which might be of value to future investigators, is also appended.

* * * * *

Introduction

MUCH information on mercury arc phenomena was published during the period 1892-1911, referring, however, to the mercury arc in glass bulbs only, while the theory of single-phase rectification was especially treated by Steinmetz and Cooper Hewitt. Over 20 years ago, the latter was actually constructing the first rectifier of a practical design which was received with much interest for a time, especially in this country. Steinmetz even gave a theoretical treatment of the two-phase rectifier and discussed the internal phenomena with the help of oscillograms. After a comparatively long period of inactivity, this problem of rectification by means of the mercury arc valve was again taken up, but this time in Europe. The large power rectifier was made possible to a great extent by the construction of an ingenious seal for use with steel tanks. Up to this time only glass vessels could be made sufficiently air-tight.

Inasmuch as in Europe alone several hundred rectifiers are already in successful operation (some of them for nearly 15 years), it may be seen that the steel-enclosed, mercury arc rectifier is equal in its state of development to the rotary converter. Of course, there are still many developments possible, especially in increasing the d-c. voltage. The latest tests in this direction promise results which as yet cannot even be foreseen. The highest d-c. voltage rectifier commercially used,—*i. e.*, 4000 volts,—has been in successful operation for over a year and a half, and tests have been made with as high as 8000 volts. Such high-voltage rectifiers, having an over-all efficiency of over 98 per cent, possess their greatest interest when considered with respect to railway electrification. Later on it will be seen that among the chief advantages of these rectifiers are not only their high efficiency, especially at partial load, but also the decrease in the cost of maintenance and operation.

Although the physical phenomena involved in the operation of the mercury arc rectifier are not fully understood, the quantitative relations upon which rectifier design is based are well established. These relations are given herein particularly with a view to their practical applications, leaving out factors which would only complicate the treatment and do not affect the final results of the computations to any great extent.

The presentation of the theory is based largely on a paper by Daellenbach and Gerecke (see Bibliography).

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Presented at the Regional Meeting of District No. 1 of the A. I. E. E., Niagara Falls, N. Y., May 26-28, 1926.

Theory

The underlying principle of operation of the mercury arc rectifier is the valve action of the mercury arc in vacuum, which permits the flow of current in one direction only, from the anode to the mercury cathode.

The fall of potential in the mercury arc is constituted of three parts, a drop of 5.7 volts at the cathode surface, a drop of 6.3 volts at the anode surface, and the drop in the arc proper which is 0.1 to 0.4 volts per centimeter of arc length. Provided the current density in the arc is not too great, the fall of potential in the arc is independent of the current and the voltage of the electrodes and depends only on the nature of the vacuum and on the nature of the electrodes. The voltage drop in a mercury arc is reduced slightly by the presence in close proximity of another arc in which the current is changing. For this reason, in polyphase rectifiers, where this condition exists during the period of overlapping of two consecutive phases, the anodes should be arranged in cyclic order so that the arc passes from anode to anode without skipping.

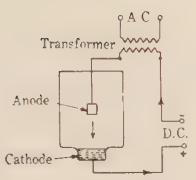


Fig. 1—Single-Anode Rectifier

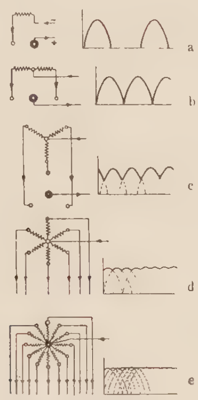


Fig. 2—Single-Phase and Polyphase Rectifiers

When connected to the secondary of a transformer and an external circuit as shown in Fig. 1, current will flow in the direction indicated when the potential of the anode is positive with respect to the cathode. When a single anode is used, Figs. 1 and 2A, current will flow only during one-half of the cycle. By using two anodes with the midpoint of the secondary of the transformer as the negative d-c. pole, Fig. 2B, current will flow over one anode during the first half of the cycle and over the other anode during the second half of the cycle. The full voltage wave is thus utilized and with a sinusoidal pulsating alternating voltage on the a-c. side a continuously flowing pulsating direct current is obtained on the d-c. side. In polyphase rectifiers with more than two anodes, Fig. 2C-E, the current will flow over the anode with the momentarily highest potential and the arc will travel from anode to anode describing a cone with its apex at the cathode.

It is seen from Fig. 2 that the larger the number of phases the better the form of the direct-current wave. However, as will be shown later, the number of phases used is limited by practical considerations. The frequency of pulsation of the direct-current wave is equal to the product of the a-c. frequency and the number of phases. These pulsations can be reduced to a negligible value by means of a choke coil in the cathode circuit.

In considering the current and voltage relations of a rectifier, the following simplifying assumptions will be made: (1) The direct-current wave is assumed to be a straight line. (2) The voltage drop in the arc is assumed to be constant at all loads. (3) The rectifier transformer ratio is assumed to be 1:1. (4) The magnetizing current of the transformer is neglected.

With these assumptions, the current and voltage relations of the rectifier will be derived: First, *neglecting the resistance and reactance of the transformer and line*; Second, *the effect of the reactance of the transformer secondary will be considered.*

Symbols. Following is a list of the symbols used and their explanations:

A Effective value of anode current
E Effective value of phase voltage, primary and secondary
E_d Average value of d-c. voltage
I Constant direct current
I_p Effective value of primary current
L Inductance per phase of transformer secondary
P Average d-c. power
P_1 Rating of transformer primary
P_2 Rating of transformer secondary
$X = 2\pi f L$ Reactance per phase of transformer secondary
$P. F.$ Power factor in line
a_1, a_2, etc. Instantaneous values of anode currents
e_1, e_2, etc. Instantaneous values of phase voltages
e_d Instantaneous value of d-c. voltage
f Frequency of a-c. supply
i_1, i_2, etc. Instantaneous values of transformer primary currents
p Number of secondary phases = number of anodes
t Time
u Angle of overlap
$x = \omega t = 2\pi f t$

1. *Voltage and Current Relations with Zero Transformer Reactance.* We shall consider the general case of a p-phase rectifier, delivering a constant direct current. I. The transformer is assumed to have zero reactance. The anodes then burn in sequence, one at a time, and each anode delivers the current I for an interval of $2\pi/p$. The anode current has the rectangular shape

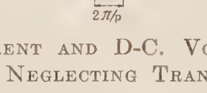


Fig. 3—Anode-Current and D-C. Voltage Waves of a p-Phase Rectifier, Neglecting Transformer Reactance

shown in Fig. 3. Its average value is I/p and its effective value

$$A = \sqrt{\frac{1}{2\,\pi} \cdot \frac{2\,\pi}{p}\, I^2} = I/\sqrt{p} \qquad (1)$$

The d-c. voltage, including the drop in the arc and the cathode choke coil, is equal to the voltage between the transformer neutral and the momentarily burning anode. Since the reactance drop is assumed to be zero, the d-c. voltage wave has the form shown in heavy outline in Fig. 3, and its average value

$$E_d = \frac{1}{2\,\pi/p} \int_{-\pi/p}^{+\pi/p} E\,\sqrt{2}\cos x\,d\,x = \frac{E\,\sqrt{2}\sin \pi/p}{\pi/p} \qquad (2)$$

The average d-c. power

$$P = E_d\,I = E\,I\,\sqrt{2}\,\frac{\sin \pi/p}{\pi/p} \qquad (3)$$

The rating of the transformer secondary windings

$$P_2 = p\,E\,A = E\,I\,\sqrt{p} = \frac{\pi/p\,\sqrt{p/2}}{\sin \pi/p} \,.\, P \qquad (4)$$

For a given transformer connection, the transformer

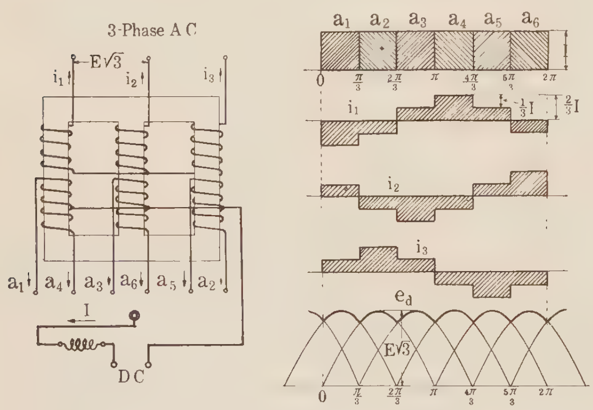


FIG. 4—ANODE AND TRANSFORMER PRIMARY CURRENTS OF 3-Y/6-PHASE RECTIFIER, USING THE DIAMETRICAL CONNECTION OF SECONDARIES

primary and line current waves can be constructed from the anode currents. The effective values of the currents as well as the transformer primary ratings can then be computed.

For illustration we shall compute the voltages, currents, and transformer ratings of a six-phase rectifier with a 3-Y/6-phase transformer using the diametrical connection of secondaries.

Six-Phase Rectifier with Three-Phase, Y-connected Transformer Primary. Fig. 4 shows a 3-Y/6-phase transformer connected to a six-phase rectifier. The numeral subscripts of the anode currents correspond to the order in which the anodes will burn. With the assumption of zero magnetizing m. m. f., the sum of the m. m. f's. around a closed magnetic path in the transformer core is zero. With an assumed 1:1 transformation ratio, we can write:

$$i_1 + a_1 - a_4 + a_6 - a_3 - i_2 = 0 \qquad (5)$$

$$i_1 + a_1 - a_4 + a_2 - a_5 - i_3 = 0 \qquad (6)$$

Also by Kirchoff's first law

$$i_1 + i_2 + i_3 = 0 \qquad (7)$$

Solving the above equations simultaneously for i_1, i_2 and i_3 we obtain

$$i_1 = -\frac{2}{3}\,a_1 - \frac{1}{3}\,a_2 + \frac{1}{3}\,a_3 + \frac{2}{3}\,a_4 + \frac{1}{3}\,a_5 - \frac{1}{3}\,a_6 \qquad (8)$$

$$i_2 = \frac{1}{3}\,a_1 - \frac{1}{3}\,a_2 - \frac{2}{3}\,a_3 - \frac{1}{3}\,a_4 + \frac{1}{3}\,a_5 + \frac{2}{3}\,a_6 \qquad (9)$$

$$i_3 = \frac{1}{3}\,a_1 + \frac{2}{3}\,a_2 + \frac{1}{3}\,a_3 - \frac{1}{3}\,a_4 - \frac{2}{3}\,a_5 - \frac{1}{3}\,a_6 \qquad (10)$$

From these expressions the primary current curves have been constructed in Fig. 4. From equations (1) and (2) and from the diagram of Fig. 4,

$$A = I/\sqrt{p} = I/\sqrt{6}$$

$$E_d = E\,\sqrt{2}\,\frac{\sin \pi/p}{\pi/p} = E\,\sqrt{2}\,\frac{\sin \pi/6}{\pi/6} = \frac{3\,\sqrt{2}}{\pi}\,E$$

$$I_p = \sqrt{\frac{1}{\pi} \cdot \frac{\pi}{3}\left[\left(\frac{1}{3}\,I\right)^2 + \left(\frac{2}{3}\,I\right)^2 + \left(\frac{1}{3}\,I\right)^2\right]}$$

$$= \frac{\sqrt{2}}{3}\,I$$

$$P = E_d\,I = \frac{3\,\sqrt{2}}{\pi}\,E\,I$$

$$P_2 = p\,E\,A = E\,I\,\sqrt{6} = \frac{\pi}{\sqrt{3}}\,P$$

$$P_1 = 3\,E\,I_p = E\,I\,\sqrt{2} = \frac{\pi}{3}\,P$$

$$P.\,F. = \frac{P}{P_1} = \frac{3}{\pi} = 0.955$$

For other transformer connections the values of currents, voltages and transformer ratings can be computed similarly. These values for various transformer and rectifier connections are given in Fig. 8. Although computed on the assumption of zero transformer reactance and several other simplifying assumptions, *the values of this table are sufficiently accurate for most practical purposes.*

From Fig. 8, it is seen that the primary and secondary of the rectifier transformer have different ratings and that the relation between alternating- and direct-currents and voltages depend on the number of phases and the connections used. *The requirement of transformers of special design is therefore evident.*

Absorption Reactance Coil. The last two columns in

Fig. 8 deal with rectifiers having an absorption reactance coil. The absorption reactance coil, Fig. 5, consists of two windings having a common core. One terminal of each winding is connected to one side of the split transformer neutral. The other terminals are connected together to the negative d-c. pole. The polarity of the windings is such that their m.m.f's. oppose each other.

This arrangement produces a strong choking effect causing both sections of the transformer secondary to deliver currents simultaneously. The effect is that the six-phase rectifier is converted into two parallel working three-phase sections, each section delivering one-half of the direct current.

As a result, the effective values of the transformer currents and the transformer ratings are reduced as seen from Fig. 8, and the regulation of the rectifier is improved as will be shown later.

Effect of Reactance in Transformer Secondary. We shall return to the general case of a p-phase rectifier.

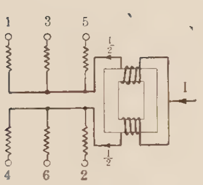


FIG. 5—ABSORPTION REACTANCE COIL

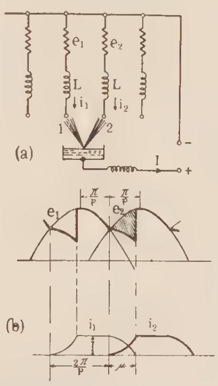


FIG. 6—ANODE CURRENT AND D-C. VOLTAGE WAVES OF A p-PHASE RECTIFIER, CONSIDERING REACTANCES OF TRANSFORMER SECONDARY

However, each phase of the transformer secondary now has an inductance L. Due to this inductance the anode currents can no longer build up and die down instantly as previously assumed, but the currents of two consecutive phases overlap. Two adjoining anodes, therefore, have their arcs going simultaneously for a short interval, constituting an electrical connection between the open ends of the windings of the overlapping phases. This condition is shown in Fig. 6A.

Anode 1 carries the full current I until the point of intersection of the voltage waves e_1 and e_2, when anode 2 strikes its arc. The instant of this occurrence will be used as the time origin for the expression of the voltages and currents.

Applying Kirchoff's second law to the closed circuit formed by phases 1 and 2, Fig. 6A,

$$e_1 - L\frac{d\,i_1}{d\,t} + L\frac{d\,i_2}{d\,t} - e_2 = 0 \qquad (11)$$

(Since the voltage drops in the two arcs are equal, they cancel each other and therefore do not enter into the above expression.)

Also

$$i_1 + i_2 = I \qquad (12)$$

$$e_1 = E\sqrt{2}\cos(\omega\,t + \pi/p)$$

$$e_2 = E\sqrt{2}\cos(\omega\,t - \pi/p)$$

Substituting for e_1 and e_2 in (11) and solving (11) and (12) simultaneously for i_1 and i_2 we obtain,

$$i_1 = I - \frac{E\sqrt{2}\sin\pi/p}{X}(1-\cos\omega\,t) \qquad (13)$$

$$i_2 = I - i_1 = \frac{E\sqrt{2}\sin\pi/p}{X}(1-\cos\omega\,t) \qquad (14)$$

Where $X = \omega\,L$

The form of the anode current waves during the period of overlapping as determined by expressions (13) and (14) is shown in Fig. 6B. The overlapping of the currents lasts until i_1 has become 0, since the valve action of the arc prevents it from ever having a negative value.

The angle of overlap u can be determined by equating to zero the expression for i_1 with $\omega\,t$ replaced by u.

$$i_1 = I - \frac{E\sqrt{2}\sin\pi/p}{X}(1-\cos u) = 0$$

from which

$$\cos u = 1 - \frac{I\,X}{E\sqrt{2}\sin\pi/p} \qquad (15)$$

From (15),

$$\frac{E\sqrt{2}\sin\pi/p}{X} = \frac{I}{1-\cos u}$$

Substituting in (13) and (14) and replacing $\omega\,t$ by x we obtain

$$i_1 = I\left(1 - \frac{1-\cos x}{1-\cos u}\right) \qquad (16)$$

$$i_2 = I\,\frac{1-\cos x}{1-\cos u} \qquad (17)$$

The effective value of the anode current may be computed by means of the diagram in Fig. 6 and expressions (16) and (17).

$$2\,\pi\,A^2 = \int_0^u i_2^2\,d\,x + I^2\left(\frac{2\,\pi}{p} - u\right) + \int_0^u i_1^2\,d\,x$$

from which

$$A = \frac{I}{\sqrt{p}}\sqrt{1 - p\,\psi(u)} \qquad (18)$$

where

$$\psi(u) = \frac{(2+\cos u)\sin u - (1+2\cos u)\,u}{2\,\pi\,(1-\cos u)^2}$$

Compare (18) with (1)

$$P_2 = p\,E\,A = E\,I\sqrt{p}\sqrt{1 - p\,\psi(u)} \qquad (19)$$

The d-c. voltage, *i. e.*, the voltage between the transformer neutral and burning anode, is now reduced by the drop in the inductance of the transformer secondary (see Fig. 6) which is equal to:

$$L \frac{d\,i_2}{d\,t} = \frac{\omega\,L\,I\sin x}{1-\cos u} = \frac{I\,X\sin x}{1-\cos u}$$

The average value of this drop

$$d = \frac{1}{2\,\pi/p}\int_0^u \frac{I\,X\sin x}{1-\cos u}\,d\,x = \frac{I\,X}{2\,\pi/p} \qquad (20)$$

The average d-c. voltage considering the reactance drop is determined from equations (2) and (20)

$$E_d = \frac{E\sqrt{2}\sin\pi/p}{\pi/p} - \frac{I\,X}{2\,\pi/p} \qquad (21)$$

$$P = E_d\,I = \frac{E\,I\sqrt{2}\sin\pi/p}{\pi/p} - \frac{I^2\,X}{2\,\pi/p} \qquad (22)$$

The transformer primary and line current waves can be constructed from the anode currents as was done previously. For a 3-Y/6-phase transformer the primary current wave can be constructed from the anode currents using equations (8), (9) and (10). The effective value of the primary current and the rating of the transformer primary can be calculated then.

Regulation. Equation (21) expresses the d-c. current-voltage characteristic of the rectifier. The first term in the expression represents the d-c. no-load voltage. The second term shows the variation of the voltage drop with load. It is seen that the larger the number of phases the greater is the voltage drop and, therefore, the poorer the regulation. It also explains how the absorption reactance coil improves the regulation. The reactance divides the six-phase transformer into two three-phase transformers having the characteristics of two three-phase transformers in parallel. By converting the six-phase rectifier into two parallel working three-phase sections, the voltage drop is reduced both on account of reduction in the number of phases and the current delivered by each section.

The transformer primary and line reactances have the same effects as the transformer secondary reactance, as far as the d-c. voltage, anode current, and transformer secondary rating are concerned, and could be replaced by an equivalent (not equal) reactance in the transformer secondary. The effect of the primary and line reactances on the transformer-primary current and rating depend on the type of primary connection used and the magnitude of the reactance.

Rectifier Transformers and Their Connections

The transformers used in connection with mercury arc rectifiers are employed not only to step-down the a-c. voltage so that a d-c. voltage of a desired value is obtained at the rectifier terminals, but they serve several other purposes as well, and, therefore, their design and connections differ from standard transformers. The factors involved in the design of rectifier transformers are given below.

The treatment under "Theory" showed that it is essential from certain points of view to have a large number of phases and anodes, respectively (see Fig. 2), in order that the voltage on the d-c. side may be practically constant. Moreover, it could be seen that the rating for which a rectifier transformer must be designed is higher than the d-c. output which is desired from the rectifier. In designing the secondary winding, consideration must be given to the fact that the root-mean-square value of the anode current is considerably higher than the total current divided by the number of anodes. Furthermore, it is essential to keep in mind that in case of a short circuit on the d-c. side, the transformer connected to the rectifier is under more severe stresses than when connected to a rotary converter under similar conditions.

The rating of the transformer for a particular rectifier can be found under "Theory," and also in Fig. 8. Its mechanical construction has to be such that the high electric dynamic forces produced between the anode currents in the windings by a short circuit in the d-c. system are taken care of satisfactorily. Although it is not easy to meet these abnormal conditions, on account of the heavily unbalanced loads which occur, resulting in axial stresses on the coils, these conditions are admirably met in the transformer described below. The coils are always kept under a certain pressure by means of a specially designed support. It is composed of pressure rings of cast steel placed above and below the windings and held together by long bolts and spiral springs, thus forming a solid unit. In order to distribute the axial pressure evenly between the low- and high-voltage windings, an auxiliary ring is placed between the steel-pressure ring and the end-distance pieces of one of the windings, making possible a proper adjustment by means of screws.

The bushings are fastened to a common terminal frame so that the cover of the tank can be removed without taking off the terminals. Reference will also be made to the electrical design of the rectifier transformer in connection with regulation and parallel operation. The voltage regulation depends entirely upon the transformer design, or upon both the transformer and the auxiliary apparatus; since the rectifier itself has no regulating properties, the connections of the windings of rectifier transformers are therefore important. In Fig. 17 A, B, C, D are illustrated various transformer connections; the open terminals of the secondary windings lead to the rectifier anodes.

The term "regulation of the rectifier" refers to the voltage drop between full load and no load at the d-c. side and for several transformer connections usually employed the regulation performance is given below:

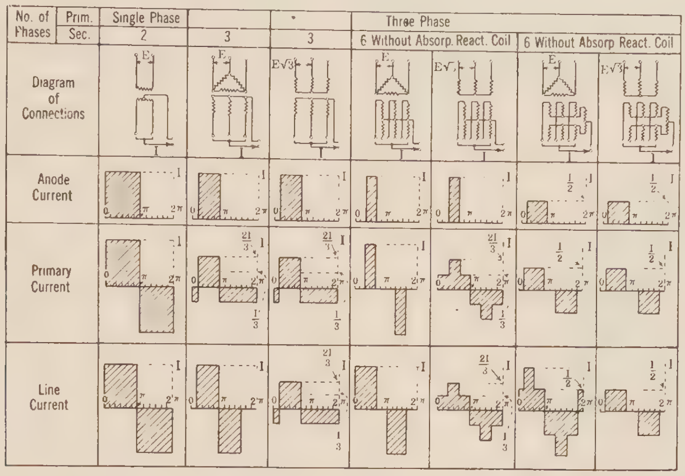
Double six-phase connection, primary three-phase,

Y or delta, usually used with an absorption reactance coil, see Figs. 8 and 17A, has a regulation of about 10 to 12 per cent without and about 4 to 5 per cent with absorption coil;

Polygon connection, primary three-phase-Y regulation about 6 per cent;

Zig-zag connection, primary three-phase-Y, regulation as for polygon connection;

Double zig-zag connection, primary three-phase Y, (used for 12-anode rectifiers or two six-anode rectifiers in parallel) regulation as for the two preceding connections.



No. of phases	Prim. / Sec.	Single-phase 2	Three-phase Delta 3	Three-phase Star 3	Delta, 6 without absorp. react. coil	Star, 6 without absorp. react. coil	Delta, 6 with absorp. react. coil	Star, 6 with absorp. react. coil
Anode current	Maximum	I	I	I	I	I	$\frac{I}{2}$	$\frac{I}{2}$
	Average	$\frac{I}{2}$	$\frac{I}{3}$	$\frac{I}{3}$	$\frac{I}{6}$	$\frac{I}{6}$	$\frac{I}{6}$	$\frac{I}{6}$
	Effective	$\frac{I}{\sqrt{2}} = \frac{I}{1.41} = 0.71\ I$	$\frac{I}{\sqrt{3}} = \frac{I}{1.73} = 0.58\ I$	$\frac{I}{\sqrt{3}} = \frac{I}{1.73} = 0.58\ I$	$\frac{I}{\sqrt{6}} = \frac{I}{2.45} = 0.41\ I$	$\frac{I}{\sqrt{6}} = \frac{I}{2.45} = 0.41\ I$	$\frac{I}{2\sqrt{3}} = \frac{I}{3.46} = 0.29\ I$	$\frac{I}{2\sqrt{3}} = \frac{I}{3.46} = 0.29\ I$
Primary current, effective value		I	$\frac{I\sqrt{2}}{3} = \frac{I}{2.12} = 0.47\ I$	$\frac{I\sqrt{2}}{3} = \frac{I}{2.12} = 0.47\ I$	$\frac{I}{\sqrt{3}} = \frac{I}{1.47} = 0.58\ I$	$\frac{I\sqrt{2}}{3} = \frac{I}{2.12} = 0.47\ I$	$\frac{I}{\sqrt{6}} = \frac{I}{2.45} = 0.41\ I$	$\frac{I}{\sqrt{6}} = \frac{I}{2.45} = 0.41\ I$
Line current, effective value		I	$I\sqrt{\frac{2}{3}} = \frac{I}{1.23} = 0.82\ I$	$\frac{I\sqrt{2}}{3} = \frac{I}{2.12} = 0.47\ I$	$I\sqrt{\frac{2}{3}} = \frac{I}{1.23} = 0.82\ I$	$\frac{I\sqrt{2}}{3} = \frac{I}{2.12} = 0.47\ I$	$\frac{I}{\sqrt{2}} = \frac{I}{1.41} = 0.71\ I$	$\frac{I}{\sqrt{6}} = \frac{I}{2.45} = 0.41\ I$
Power factor in line		$\frac{2\sqrt{2}}{\pi} = \frac{1}{1.11} = 0.90$	$\frac{3\sqrt{3}}{2\pi} = \frac{1}{1.21} = 0.83$	$\frac{3\sqrt{3}}{2\pi} = \frac{1}{1.21} = 0.83$	$\frac{3}{\pi} = \frac{1}{1.05} = 0.955$	$\frac{3}{\pi} = \frac{1}{1.05} = 0.955$	$\frac{3}{\pi} = \frac{1}{1.05} = 0.955$	$\frac{3}{\pi} = \frac{1}{1.05} = 0.955$
D. C. voltage		$\frac{2\sqrt{2}}{\pi} E = \frac{E}{1.11} = 0.90\ E$	$\frac{3\sqrt{6}}{2\pi} E = \frac{E}{0.855} = 1.17\ E$	$\frac{3\sqrt{6}}{2\pi} E = \frac{E}{0.855} = 1.17\ E$	$\frac{3\sqrt{2}}{\pi} E = \frac{E}{0.74} = 1.35\ E$	$\frac{3\sqrt{2}}{\pi} E = \frac{E}{0.74} = 1.35\ E$	$\frac{3\sqrt{6}}{2\pi} E = \frac{E}{0.855} = 1.17\ E$	$\frac{3\sqrt{6}}{2\pi} E = \frac{E}{0.855} = 1.17\ E$
Transformer rating	Sec.	$\frac{\pi}{2} P = 1.57\ P$	$\frac{\pi\sqrt{2}}{3} P = 1.48\ P$	$\frac{\pi\sqrt{2}}{3} P = 1.48\ P$	$\frac{\pi}{\sqrt{3}} P = 1.81\ P$	$\frac{\pi}{\sqrt{3}} P = 1.81\ P$	$\frac{\pi\sqrt{2}}{3} P = 1.48\ P$	$\frac{\pi\sqrt{2}}{3} P = 1.48\ P$
	Prim.	$\frac{\pi}{2\sqrt{2}} P = 1.11\ P$	$\frac{2\pi}{3\sqrt{2}} P = 1.21\ P$	$\frac{2\pi}{3\sqrt{2}} P = 1.21\ P$	$\frac{\pi}{\sqrt{6}} P = 1.28\ P$	$\frac{\pi}{3} P = 1.05\ P$	$\frac{\pi}{3} P = 1.05\ P$	$\frac{\pi}{3} P = 1.05\ P$
	Aver.	1.34 P	1.35 P	1.35 P	1.55 P	1.43 P	1.26 P	1.26 P

Fig. 8—Voltage and Current Relations for Various Rectifier Connections, Neglecting Transformer Reactance and Resistance Drops

Construction and Mechanical Details of Power Rectifiers

A cross-section of a Brown Boveri rectifier of recent design is shown in Fig. 10 and described below, although reference will be made to other makes when these differ in some essential point from the above mentioned make.

The large number of different types developed during the years of experimenting have now been condensed into three commercial types. The main differences between these are the difference in the sizes of the various parts, the spacing of the anodes and cathode, and the method of anode cooling. The foundation is very light compared to that required for rotary converters. A special earthquake-resisting foundation has also been developed, which successfully keeps the vacuum piping and other delicate parts intact, even in the countries most frequently subject to seismic disturbances. Six insulating feet, resting on the cast-iron foundation ring, support the rectifier proper. If for any reason it is impossible to lift the rectifier into position, the foundation ring is provided with casters, see Fig. 11, which enable the rectifier to be moved to the desired position. The casters are provided with means for raising the rectifier off the floor while moving it and for lowering it to the floor when it has been put into place.

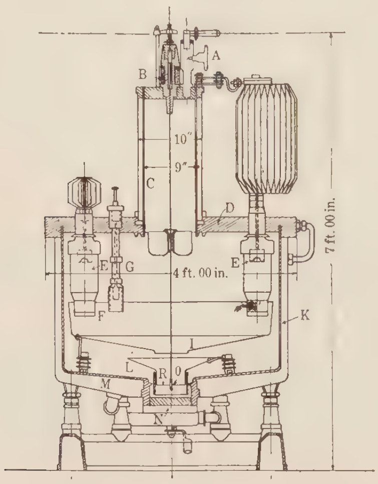


Fig. 10 —Cross-Section of a Rectifier

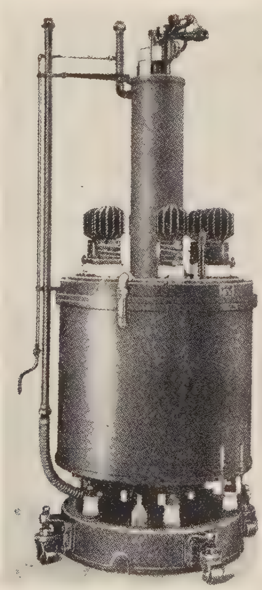


Fig. 11 —General View of a Rectifier

Cylinder. In Fig. 10 the cylinder K, made of welded steel, is closed by the anode plate D, which supports the main anodes E, the excitation anodes G, and condensing cylinder C, at the top of which is mounted the ignition device. The cathode consists of a quantity of mercury in the receptacle R. From this the electrons travel through the openings in the funnels L and I, through the so-called arc guide F, to the anode E. The funnels L and I are insulated from each other and from the rest of the rectifier by means of special insulators, visible in the drawing. The arc guide F, shown in detail in Fig. 12, has baffle plates so arranged that no secondary high-vacuum phenomena at the cathode can influence the performance of the anode.

The cooling water enters the rectifier at N, cooling the cathode and the main cylinder, which is specially treated to resist the action of the water for an indefinite period of time. The water then passes upward, through the anode plate D, into the jacket surrounding the condensing cylinder C, whence it is discharged.

The condensing cylinder C serves to cool the mercury vapor so that it becomes liquid and flows down along the walls of the cylinder into a trough, from which it is brought to a point near the wall of the main cylinder K, but outside the aprons L and I, and thence flows back into the cathode receptacle at the bottom of the main cylinder. To the top of the condensing cylinder is attached the ignition plunger, with its solenoid B, which in starting the rectifier acts upon the small iron piece just above it. The pipe to the vacuum pump also leaves the top of the condensing tower, being sealed in the same way as the current conductors.

Anodes. The main anodes are insulated with special porcelain bushings, the shape of which depends upon the voltage for which the rectifier is to be used. The shape of the anodes themselves is shown by the dotted lines. They are made of specially treated steel which has been found, after exhaustive tests, to be best suited to this purpose. The design of the anode cooling system for rectifiers to be used with voltages up to 1600 volts is shown on the right-hand side of the illustration, while the construction of the anodes for voltages as high as 3000 volts is shown on the left-hand side.

The difference in the cooling devices for the two types of rectifiers can easily be understood by taking into consideration the fact that the voltage drop of a rectifier is practically constant for all voltages. It follows, therefore, that while the heat losses in a 200-volt, 200-kw. rectifier are about 20-kw., in a 2000-volt, 200-kw. rectifier they are only about two kw. or about one-tenth of the low-voltage rectifier losses.

The excitation anode with its arc guide is shown on

the left-hand side of the drawing—its function is explained later on.

Like the inner surface of the cylinder K, and all other metal parts inside the cylinder, the anode surfaces are treated in such a way that all occluded air and other gases can easily be removed. This shortens appreciably the time required for forming the rectifiers (about which more is said later on) before they can be put into service. The spacing of the anodes, their shape, and the special manner of treating them, make the rectifier insensible to momentary short circuits, as well as to heavy overloads, which would be disastrous in the case of rotary converters.

Sealing. The seals in the above mentioned make of rectifier are secured by means of mercury, and hence they are not only perfectly air-tight, but they also are not sensitive to the action of the mercury vapor and other gases which are developed in the cylinder. Furthermore, they can be equipped with a visible indicating device.

The Allgemeine Elektrizitats Gesellschaft of Berlin employs a composite packing of aluminum and lead, the former dealing with the high vacuum while the latter forms the seal against the atmosphere. An intermediate space is provided between the aluminum and lead seals which is itself evacuated, and serves to distribute the pressure in such a way that each seal has to deal only with a part of the total pressure difference. For inspection and testing purposes, however, it is necessary to fit each seal with a vacuum pipe, and in case of a leaky cylinder each vacuum pipe of the series must be connected to the gage in turn until the faulty seal has been discovered. Moreover, thorough investigation revealed the fact that mercury vapor and other gases will affect such metal seals to a certain extent, and unless iron is used, an amalgam is formed which may destroy the seals in a very short time. Furthermore, these investigations showed that due to aging of the metals, all inner elasticity is lost after a year or two and that repeated tightening after successive intervals will not remedy the trouble.

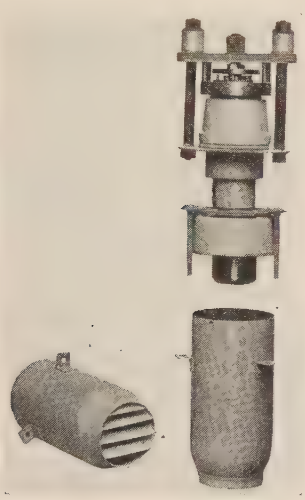


Fig. 12—Anode with Arc Guide

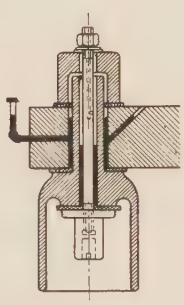


Fig. 13—Mercury Seal with Indicating Gage.

The General Electric Company's glass seal which was recently mentioned in an article on rectifiers may prove to be very effective, and it will be interesting to learn how it stands up in practise. The description of it given in the article did not contain enough information to permit a thorough discussion of it. However, the disadvantage of these seals seems to be that there is no possibility of detecting any leakage, and that when the anodes are removed the seals are destroyed.

The construction of the Brown Boveri seal is shown in detail in Fig. 13. The joints are first fitted with special elastic washers, and thorough investigation, carried on for an extended period, showed that an asbestos washer (double cross-hatched shading) was most suitable. The mercury (solid shading) is then poured into the annular spaces between the anode plate and the insulating bushing, and the insulating bushing and the central conductor, respectively, thus sealing the vacuum, while the asbestos keeps the mercury from flowing into the cylinder.

One of the most important features of the mercury seal is the fact that in case any mercury should filter past the asbestos packing it would only find its way to the mercury cathode at the bottom of the cylinder, doing absolutely no harm. At the same time the leak would be indicated at the mercury gage with which each seal is equipped. The gage, therefore, makes it possible to check instantly the condition of each seal, and if necessary the bolts can be tightened before the vacuum is broken.

Ignition and Excitation. The ignition of the arc is accomplished by means of a small plunger, O, usually located, as in Figs. 10 and 14, within a few millimeters of the surface of the mercury cathode in the receptacle R and connected to a special metal rod extending from the top of the condensing cylinder. This plunger is controlled by the solenoid B, located at the top of the condensing cylinder, which pulls the plunger into the mercury cathode against the action of a spring. As soon as the plunger touches the mercury, the solenoid is de-energized and the plunger is withdrawn. In a fraction of a second an arc is drawn between the mercury cathode and either the excitation or the main anodes, provided the vacuum in the cylinder is sufficiently high and a load is connected to the d-c. circuit.

When working at very light loads the main arc has a tendency to become unstable, and may be extinguished. Therefore, when the d-c. demand is highly fluctuating, as in traction systems, rolling mills, etc., where the current might drop below the value which is necessary to maintain the arc, the cylinders are equipped with excitation anodes. A cross-section through such an anode G is shown in Fig. 10 and it is indicated in Fig. 14, where it is denoted by A_e. The construction of it is similar to that of the main anode, and it is located at about

three-quarters of the total distance between the cathode and the main anode. Much investigation had to be done in order to find the proper location and shape of the excitation anodes so as to prevent condensation of mercury at the main anodes in case the main arc should be extinguished for a considerable length of time. The latest development in this line is the recently developed pure *a-c. ignition device,* by which means the necessity for a special ignition converter is obviated. Trial tests in two Swiss installations demonstrated

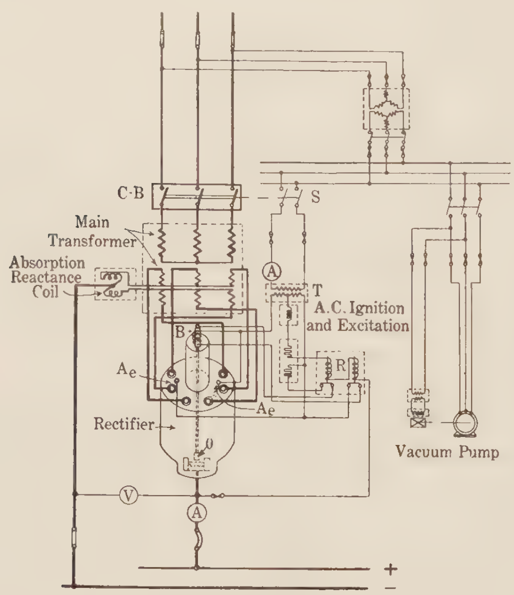


Fig. 14—Typical Diagram of Connections, Showing a Novel Type of Ignition and Excitation Equipment

the superiority of this novel method which is of the utmost importance in connection with fully automatic substations. A full description of a plant equipped with such an ignition and excitation apparatus is given below under "Operation."

Auxiliary Devices

On a rectifier equipment of the simplest form there is only one important auxiliary provided, namely, the vacuum pump and measuring gages illustrated in Fig. 16A. A high vacuum is absolutely essential to the satisfactory operation of the plant.

The pumps used are of special design, and very efficient, so that there is no difficulty in producing a high vacuum in a properly sealed rectifier cylinder. There are several types of vacuum pumps in use, but owing to the scope of the subject, a description of them will not be given here. Just as essential as the pump for producing the vacuum is the device for measuring it. An improvement of the utmost importance has recently been made in this line, which will be described below.

The familiar McLeod mercury column gage used in connection with rectifiers and in laboratory work has been superseded by a direct-reading hot-wire vacuum gage which in size and purpose is similar to the shunt of a precision millivoltmeter.

It may be recalled that McLeod's gage is based upon the fact that the pressure of a perfect gas times its volume is always constant. This law of Boyle's holds true, however, only for perfect gases, and therefore the use of the above gage furnishes no information about the other gases and the vapors of water, mercury, etc., which the cylinder might contain. Another disadvantage of this gage is the fact that it is not direct reading, and cannot be used for automatic station control.

The development of the new direct-reading gage, therefore, made it possible for the first time to study scientifically several phases of the mercury arc rectifier and the influence of the degree of vacuum upon its operating conditions. The latest improvements in the operation of rectifiers are a direct result of the increased ability, made possible by this instrument, to measure high vacuums.

Novel Hot-Wire Vacuum Gage. The arrangement of the direct-reading measuring device as shown in Fig. 16A and B consists of the following important parts: a hot-wire sealed-vacuum gage 1, illustrated by Fig. 16A, a resistance 4, a shunt 5, and a precision moving coil voltmeter 6. The connection to the vacuum piping of the rectifier is shown at E.

The working principle of the hot-wire vacuum gage is based upon the fact that the thermal conductivity of gases depends upon the gas pressure. If two bodies at different temperatures are placed opposite to one

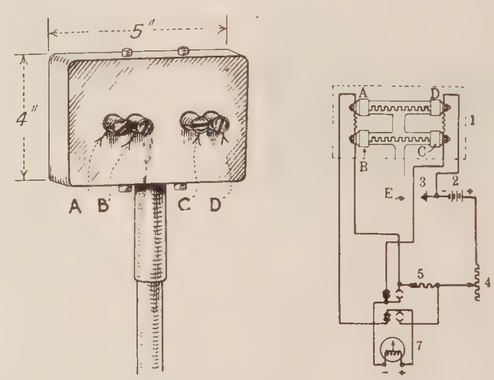


Fig. 16A—Novel Electric Hot-Wire Vacuum Gage

B—Diagram of Connections for Gage and Recording Instrument

another, a heat transfer takes place from the warmer to the colder body, partially by radiation and partially by conduction. It must be kept in mind that (1) the radiation is independent of the gas pressure existing between the two bodies, and that (2) the heat conductivity depends mainly upon the respective pressures. In an absolute vacuum the latter are zero. At first the conductivity rises in proportion to the increasing gas pressure, while the latter approaches asymptotically a constant limit of value. In the range of small pressures,

the thermal conductivity is, therefore, a measure of the gas pressure.

The gage consists of four resistance wires connected together like a Wheatstone bridge. The wires stretched between the terminals *B C* and *A D* are located in the vacuum, while the wires *A B* and *C D* are exposed to the atmosphere, as shown in Fig. 16B. They are electrically heated with a constant current of about 100 milliamperes. When the branches *B C* and *A D* of the bridge are heated, their ohmic resistance and the pressure difference between the points *A* and *C* increase in proportion to the vacuum. Since this potential difference varies with the degree of vacuum, the deflection of the meter varies in proportion, giving a continuous indication of the vacuum in the rectifier cylinder. On account of the special bridge connection, fluctuations of the room temperature have practically no influence on the reading of the vacuum gage. For the safe operation of the voltmeter, the lead from terminal *D* is grounded at 3.

The millivoltmeter is designed as a contact voltmeter with two adjustable contacts which are set for predetermined low and maximum values of the vacuum, and, therefore, can be used for the automatic control of the air-pump set, making possible a full automatic control of a mercury arc rectifier substation.

The hot-wire vacuum gage is connected to the vacuum piping by means of a flange and a high-vacuum stuffing box. When connecting the apparatus, the vacuum gage is first fitted with the stuffing box, after which both parts are connected to the vacuum piping, and finally the stuffing box filled with the sealing mercury. This is essential in order to prevent the outer and inner parts of the vacuum gage from coming into contact with the mercury or the mercury vapor.

The arrangement with the battery 2 furnishing the direct current for the bridge has been superseded by an arrangement allowing the use of alternating current taken from the normal control circuit of the plant. The principle upon which the measuring device is based is the same, but this arrangement does away with the battery and makes the apparatus very simple and consequently fool-proof.

Next in order would be mentioned the ignition converter providing an independent source of current to start the arc. But recently made improvements on the Brown Boveri type rectifier made such a converter unnecessary, and, as can be seen under the next heading, starting is accomplished by means of alternating current furnished from the control circuit.

Cooling. In order to carry off the heat produced by the arc, the rectifier cylinders are usually cooled by means of water, as described above. In case fresh water of sufficient quantity and purity is available near the plant, no auxiliary device is necessary; otherwise, a small pump is required. This pump, usually electrically driven, continuously circulates the water through a recooling system, which consists of radiators mounted near the rectifier installation.

Another auxiliary of importance is the absorption or regulation reactance coil placed in the neutral point of the main transformer, its function being to limit the inherent regulation of the complete plant to a reasonable figure—usually of the order of five per cent from full to approximately no load. Without this coil the regulation may be as high as 10 to 12 per cent unless special transformer connections are used. Further details are given under "Theory" and "Transformers."

Operation of Rectifiers: Single, in Groups, and with Rotary Converters

Before a mercury arc rectifier can be placed in service, a certain "forming" process has to be carried out. The forming itself consists of expelling the gases occluded in the metal parts of the rectifier, chiefly in the anodes. To be able to conduct this process intelligently, it is essential to have a measuring gage which indicates not only the pressure of the perfect gases, but also the pressure of other gases and vapors present. Some of the late t improved methods along this line have to be credited to the hot-wire vacuum gage previously described.

In order to shorten the forming process, it is important that all moisture and humidity be removed from inside the tank beforehand. This is done by the application of high heat, either by passing current through the rectifier, or by circulating hot water. If an electric current is used, it is gradually increased from a low value until the anodes are brought to maximum heat. At the same time the vacuum pump exhausts the gases liberated from the anodes. Various schemes were tried out to faciliate and hasten this preparation for the forming process. This preparation is of the utmost importance in that the gases occluded in the metals can otherwise not be expelled at all, or only very slowly, when the cylinder is being finally evacuated.

Forming is usually started by treating each anode individually, the d-c. energy being dissipated in a small grid resistance. This is followed by six-phase forming, during which time the rectifier may be connected to a commercial load. The time spent in forming at the factory varies between two and three days, and generally a similar procedure is carried out during erection at the power plant or substation. The forming process should be continued day and night with as few interruptions as possible, and therefore needs careful attention. It is understood that during this process the pumps have to be in operation continually, and also for a further length of time after the rectifier has been placed in service. Both processes have been very carefully worked out in every detail, and their successful application is a direct result of long and elaborate experimenting.

One of the difficulties that had to be overcome in connection with the satisfactory operation of the mer-

cury arc rectifiers, both during forming and in actual service, was internal flashing-over or back-firing. Such internal disturbances, which paralyze the valve effect, were overcome after years of investigation. They have occurred sometimes when the forming process was not carefully carried out, or because of neglect in properly checking the material, especially that used for the anodes. However, if the proper precautions are not taken, such disturbances can occur during the forming process even now.

Ignition and Excitation Control of Novel Design. A typical diagram of connections is given in Fig. 14, which shows all the auxiliary gear of a rectifier controlled and operated in an ingenious way. The outstanding feature is that the controlling, starting, etc., are accomplished by means of alternating current, which is taken from the usual control circuit, fed from the high-voltage line through an auxiliary transformer. No direct current is needed to strike the arc nor to control the ignition anode. The fact that it was possible to dispense with the d-c. source, usually a specially designed converter set, and the development of a simple control arrangement for both ignition and excitation, account for the very simple layout of such a plant, which can be made fully automatic by merely adding two special relays.

The rectifier starts automatically as soon as the circuit-breaker $C\,B$ on the high-voltage side connects the main transformer to the high-voltage line. This breaker is mechanically coupled to the switch S, which connects the excitation transformer T to the a-c. control circuit. As soon as the switch S is closed, the ignition solenoid B, see also Fig. 10, is energized, and the ignition anode consisting of plunger O is immersed in the mercury cathode, thereby closing another circuit through the right-hand secondary winding of the excitation transformer T and the two relay coils R. The right-hand relay, as soon as it is energized, in turn opens the ignition coil circuit, and the ignition anode is withdrawn from the mercury cathode by the action of the spring, thus striking an arc and enabling the rectifier to pick up load on the d-c. side at once. Should it happen that the polarity is not correct, the arc is immediately extinguished and the right-hand relay deenergized again, thus causing a repetition of the ignition process until the arc has the correct polarity. As soon as the excitation anodes are working the ignition circuit is broken by the action of the left-hand relay R.

The time which elapses from the moment the circuit-breaker relay receives an impulse to close the circuit breaker to the moment the rectifier is able to handle load is usually less than two seconds. The value of such a simple and quick operation cannot be appreciated enough in connection with automatic substations, as well as in other ways. For instance, in substations equipped with rotary converters, it is possible to have a rectifier as a spare set which can instantly be placed into service to take care of peak loads of such short duration that the rotary converters as reserve units would miss them because of the time involved in starting them.

The d-c. voltage is controlled either by step-by-step regulation from the primary side of the transformer or by an induction regulator, hand or automatically operated. The arrangement with the induction regulator is decidedly preferable for lighting supplies, as the voltage can be varied smoothly and to any extent. For the case of traction supplies, and where the question of regulation is not of primary importance, the rectifier can be given a shunt characteristic with a four- or five-per cent rise of pressure with falling load, by the use of specially designed transformers or an *absorption reactance coil* connected in the neutral of the main transformer; see Figs. 5 and 14. Reference to the latter arrangement has already been made under "Theory" and further details of these two methods will be given below.

Parallel Operation. It is possible to feed two rectifier cylinders from one main transformer and in such a case it is essential that each cylinder takes its proper share of the total load. Moreover, a number of rectifiers, all fed from the same primary supply, must be able to operate in parallel with each other. Furthermore, a rectifier might be added to an existing d-c. plant, and have to operate in parallel with existing rotary converter or mercury arc rectifier units. In all these cases certain conditions must be fulfilled in order that the units may supply power to the same bus-bars without interfering with each other, and that each may take a proportionate share of the total load. In considering the conditions necessary for satisfactory parallel operation of rectifiers, it has to be kept in mind that the rectifier cannot feed back to the a-c. line, and also that the inherent load characteristics of rectifiers are somewhat different from those of other converters. Some of the essential considerations relative to these facts are given below.

For all practical applications of rectifiers it can be assumed that the voltage drop in the arc in vacuum decreases with increasing current, and the load characteristic is therefore similar to that of an over-compounded d-c. generator. From the above, it can easily be seen that rectifiers feeding the same bus-bars and connected in parallel to the same source of alternating current may not operate satisfactorily. To meet this condition, a sufficiently large inductance has to be inserted in the anode circuit of each rectifier so as to obtain a suitable load characteristic which assures satisfactory parallel operation of each cylinder over a given range of load. For instance, a correctly dimensioned choke coil can be used to obtain such an inductance. Incorporating the arrangement of the connections shown in Fig. 17B, the inductance or the flux set up in the choke coil can be limited to that part produced by the difference in the anode currents. The same

effect can be obtained by utilizing that part of the main transformer inductance which corresponds to the stray field, by using either a separate transformer for each rectifier, or a double six-phase arrangement, as given in Fig. 17A and C, respectively. However, the inductance set up in this way must be large enough to impress such a high voltage across the electrodes of a rectifier working in parallel with others but not taking a share of the load which will force it to pick up some of the load. The actual arc voltage, therefore,

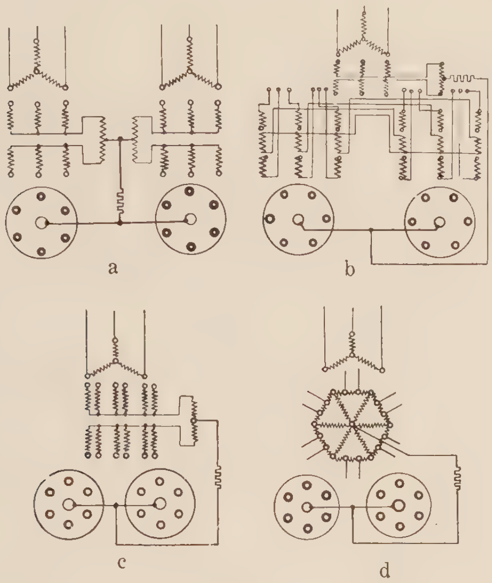


FIG. 17 A, B, C, D,—DIAGRAMS OF CONNECTIONS OF TWO RECTIFIERS IN PARALLEL

is less than the ignition voltage, and when several rectifiers are operating in parallel the unit having the lowest ignition voltage consequently picks up the load before the others. The voltage drop necessary for the operation outlined above cannot efficiently be obtained by means of ohmic resistance, and therefore methods such as those mentioned above for inserting an inductance into the anode circuit had to be developed so as to produce a satisfactory characteristic. As soon as all the rectifier units are taking their share of the load, their parallel operation is subject to the general conditions already stated. For comparison, all the methods of connection used to effect the desired characteristic for rectifier plants with more than one cylinder are given below, and are illustrated in Fig. 17A, B, C, D. In Fig. 17A, the effect is produced by making use of the leakage field of the main transformer; in Fig. 17B, by inserting a choke coil; in Fig. 17C, by means of the leakage field of the secondary winding only; and finally, in Fig. 17D, by doubling the number of phases on the secondary side.

As already pointed out, it is also essential that each unit take a proportionate share of the load when working in parallel. Two units are assumed to have falling-load characteristics E_1 and E_2, illustrated in Fig. 18. In can easily be seen that the distance between the two points of intersection of any horizontal straight line with the characteristics of the two sets gives the total current, I, supplied. The distance from the middle vertical line to the points of intersection gives the currents supplied by sets No. 1 and No. 2, respectively. The voltage of the two parallel working units is indicated by E. From this curve it is evident that an increase of the total load will be distributed according to the slope of the load characteristic.

It is sometimes desirable to have a rectifier working in parallel with rotary converters or motor generators. The efficiencies of the two latter types of converters are lower at overloads and at partial loads than the efficiency of the rectifier. In order to obtain, therefore, a good annual average efficiency for the plant, it is desirable to design these two types of converting devices for such load characteristics that in parallel operation the rotary converter or motor generator is always working at practically full load, while the fluctuating peaks are taken care of by the mercury arc rectifiers. Assuming that the load characteristic of the motor generator is shown on the right-hand side of Fig. 18, and the load characteristic of the mercury arc rectifier on the left-hand side, it is evident from the figure that the rectifier will take by far the larger share of a given increase in load.

Efficiency and Power Factor. Apart from other considerations, the outstanding electrical characteristic of the rectifier is its efficiency, which remains nearly constant at all loads; but to obtain the true commercial efficiency we must include all losses between the high-tension terminals of the transformer and the d-c. busbars. These losses are the losses in the transformer, excitation equipment, vacuum pump, and reactance coils. The constant efficiency of the rectifier alone is due to the drop in the arc being approximately constant

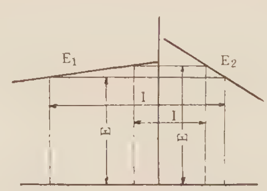


FIG. 18—PROPORTIONATE SHARE OF THE TOTAL LOAD BETWEEN A RECTIFIER AND A MOTOR GENERATOR

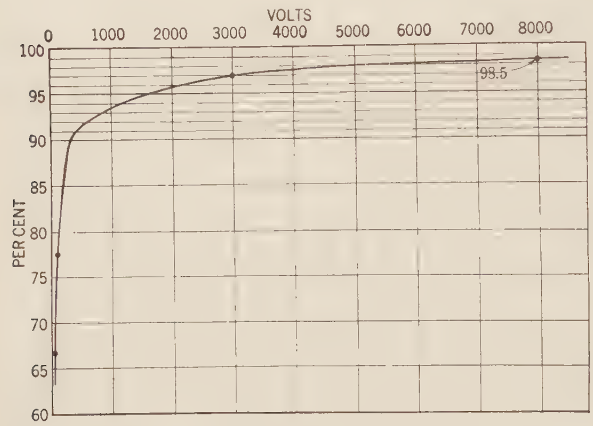
under all load and pressure conditions. This drop varies roughly between 16 and 23 volts according to the size of the rectifier, and is influenced by the vacuum to which it is directly proportional. The actual amount of watts dissipated in the rectifier is, therefore, simply the total drop multiplied by the current for any particular load, which gives a constant efficiency under all conditions. Thus when operating at 500 volts, direct current, the efficiency of the rectifier is represented by

$$\frac{500}{500 + 20} = 95.5 \text{ per cent.}$$

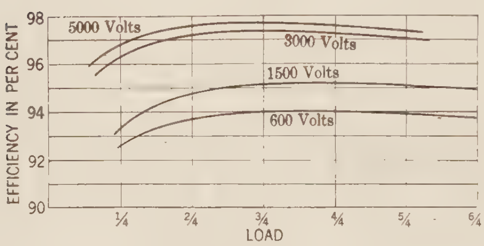
These indications show that the higher the d-c. voltage, the better will be the efficiency. For voltages up to 8000 volts, efficiency curves are plotted in Fig. 19A.

The over-all efficiency over the whole working range for 600-, 1500-, 300-, and 500-volt rectifiers of standard types is shown in Fig. 19B.

In general the power factor varies between 90 and 95 per cent. Reference was made to this under



A



B

FIG. 19A,-B—OVER-ALL EFFICIENCIES OF RECTIFIERS FOR VARIOUS VOLTAGES

"Theory" and since it depends to a great extent on the external circuit further considerations are omitted.

Overloads. It is the very high momentary overloads that the rectifier can deal with that makes it preeminently suited for traction conditions where the average load is below full load. The consequence of this is that rather smaller normally rated sets can be employed than if, for instance, rotary converters were used.

Traction rotaries must necessarily be amply rated; otherwise commutator trouble will be experienced under very heavy overload or short-circuit conditions. Sometimes this measure does not do, and some special schemes of load protection have to be employed.

Extensive load and short-circuit tests on rectifiers showed that practically any overload can be handled for a certain time with a complete absence of any bad effects on the rectifier proper.

As there are no moving nor wearing parts, the life of the rectifier is still unknown as none of the rectifiers installed more than 12 years ago have shown any signs of deterioration as yet. The arc takes place in a vacuum, and therefore there is not any appreciable chemical effect on the anode or on the cylinder. No change either in the size or the shape of the anodes or of the inside surface of the cylinder that would in any way affect the operation of the rectifier could be observed. On the contrary, experience has shown that the longer the rectifier is in operation the better are its efficiency and its overload characteristic. The vacuum pump runs for such brief periods of time, and so infrequently, that the wear on its moving parts is negligible, while the development of the a-c. ignition has done away with any other rotating parts.

ADVANTAGES OVER ROTARY CONVERTERS

The floor space usually occupied by rectifiers is about the same as that required for rotary converters for d-c. voltages up to about 600 volts. Above that, the space required is considerably less. Special foundations are not required for any voltages except what is needed to bear the stationary weight. For this reason, and due to the fact that the operation of the rectifier is noiseless, new substations need only be of the lightest

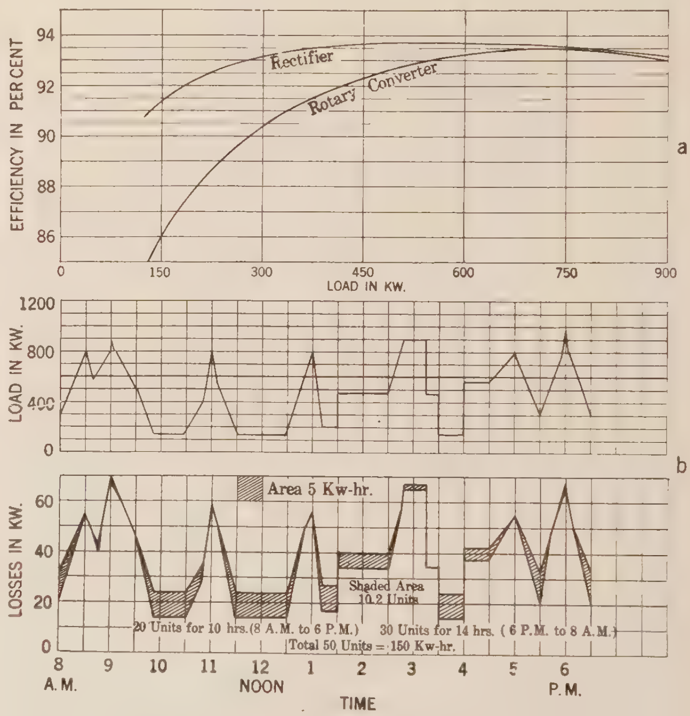


FIG. 21A—EFFICIENCY OF A 600-VOLT 600-KW. ROTARY CONVERTER AND MERCURY ARC RECTIFIER

B—LOAD CHART AND REDUCTION IN LOSSES BY THE USE OF MERCURY ARC RECTIFIERS INSTEAD OF ROTARY CONVERTERS

construction, and substations can, therefore, often be placed in locations that would not be at all suited for the installation of rotating machinery because of the vibration and noise.

Starting. Among the most striking advantages of the mercury arc rectifier over the rotary converter is the simplicity of the starting procedure. It takes a few seconds only to ignite the arc and put the rectifier

into service. This makes it preeminently adapted to automatically controlled substations. Since a rectifier has no standby losses, like a rotary converter, it can be generally left connected to the high-voltage supply, and in case of a short circuit at the primary side of the transformer, the rectifier disconnects itself from the network at the moment the arc extinguishes, and it will pick up the load as soon as the a-c. voltage is restored. However, even in manually operated substations, the attendance is greatly reduced, as will be explained at length later on.

Efficiency. To illustrate what the superiority of the rectifier efficiency really means, especially the efficiency at partial loads, a typical case of an actual railroad in the United States has been taken and the annual saving effected worked out on the basis of the daily-load curve. The curve in Fig. 21A shows the comparative efficiency of mercury arc rectifiers and rotary converters for 600-volt direct current. The conservative efficiency curves do not alter the comparative losses of the two classes of equipment nor the saving effected. The difference in the losses for the two sets is represented by the shaded area between the two lower curves of Fig. 21B and if this is averaged

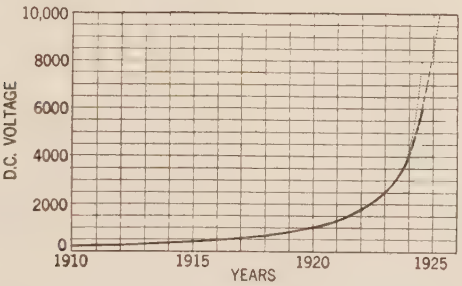


Fig. 22—Maximum D-C. Voltages of Rectifier Installations in Service and in Laboratory Tests

over 24 working hours it will be found that the losses of the rotary converter exceed those of the rectifier by about 125 kw-hr., representing, at a current cost of one cent per kw-hr., an annual saving of approximately $450 for a 600-kw-hr. mercury arc rectifier substation which represents half the interest on the investment required for such a substation.

As shown in Fig. 19A, the efficiency of a rectifier increases with the voltage; so these savings would increase appreciably at the high voltages. But even at the comparatively low voltage for which the above figures were computed the saving is worth considering. For a d-c. voltage of 1500 volts the annual saving would be over $1000.

As d-c. motors for terminal pressures of 2000 volts can be built to operate with perfect satisfaction, there is no reason why d-c. line pressures of 4000 volts cannot become widely adopted for railway service. In fact, the Torino-Lanzo-Ceres Railway in Italy has already been using that voltage for some time, and has obtained the best kind of service from its rectifier.

Needless to say, such voltages would be impracticable with rotary converters. The increase in the voltages on the d-c. side successfully used with rectifiers during the past 15 years is shown by the heavy line in Fig. 22, while the broken line shows the voltages which have been tested successfully at long trial tests, and the light dotted line, the voltages obtained during short laboratory tests. Following the extension of the voltage curve, it may be concluded that the next few years will possibly give us rectifiers furnishing direct current at pressures suitable for high-power transmission.

Another advantage of note is the fact that for the parallel operation of rectifiers there is no elaborate synchronizing procedure required. Since polarity indicators are also not needed, another possible source of trouble is eliminated. These facts again decrease the amount of special equipment necessary for an automatically or remotely controlled substation, while in a manually operated substation the attendant's duties are further reduced.

Automatic Control. The equipment for the full automatic operation of mercury arc rectifier substations costs less than half as much as for a rotary converter substation of the same capacity. Not only is the equipment cheaper, but because it is also simpler a better operation is assured.

The automatic operation of the vacuum pump is likewise an important advantage of the rectifier equipment. The vacuum gage previously described opens and closes the pump-motor circuit independently of the operation of the rectifier set itself, and always maintains the vacuum at the proper stage for immediate starting.

Making allowance for interest, depreciation, and taxes on the additional investment required for full automatic control of rectifier substations, and taking into consideration the salaries for high grade inspectors to look after the automatic equipment periodically, there will be effected a saving of $500 per year even in a small substation of only 600-kw. capacity.

Another great advantage accruing from the use of mercury arc rectifiers is the fact that changes in voltge can be made without any change in the rectifier. For instance, a railroad equipped for using 600-volt direct current can be changed to 1200-volt direct current merely by changing the connections of the transformers, and making no changes whatever in the rectifiers. Needless to say, this could not be done with rotary converters. Furthermore, the additional traffic that can be handled by making this change would represent another great advantage, all without any extra cost except the slight additional expense of having the transformers equipped with taps for making the change in the connections. As mentioned before, these rectifiers are able to withstand short circuits for a few moments without any harm, and can stand the severest overloads, taking instantaneously currents of even three times the normal value.

As an example of the short-circuit current one of the high-voltage rectifiers is capable of dealing with, it may be mentioned that a rectifier the normal capacity of which is 1800 volts and 400 amperes successfully passed a momentary current of 8700 amperes and was able to resume operation immediately upon clearing the short circuit. Sixty similar short circuits were applied within two days, after which the rectifier was opened and found to be in precisely the same condition as when sealed prior to these tests. In another instance, 10 short circuits were applied at one-minute intervals, and again there were no deleterious effects.

As mentioned under "Operation," the wear on the rectifiers is practically negligible.

The author gratefully acknowledges the valuable suggestions and assistance of Mr. Harold Winograd.

Abridgment of

Law of Magnetization

BY S. L. GOKHALE[1]

Member, A. I. E. E.

Synopsis.—*The purpose of the study which constitutes the subject matter of this paper was to investigate the reliability of Frolich's law of magnetization near saturation.*

For the last forty years, Frolich's law has been accepted as the most reliable expression representing the relation of magnetizing force to the magnetic induction produced thereby in ferro-magnetic materials. In the course of the study it was found that the law is not as reliable as it is generally believed to be, particularly for purpose of computation of saturation value. It was also found in the course of the same study that this part of the curve follows the law,

$$B - H = S\,(1 - b\,e^{-aH}) \quad . \; . \; . \; (\textit{equation } \mathbf{30\text{-}2})$$

more closely than any other law yet formulated. This law and Frolich's law are both in harmony with Weber's theory of molecular orientation. (See equations **24**, **25**, **26**).

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1. Purpose of the Investigation and Plan of Presentation of Results

THE progress of scientific and industrial development of production, distribution, and control of electrical energy depends very largely on the knowledge and understanding of the laws representing the relation of electric current to magnetism. During the last hundred years, various attempts have been made to obtain correct information about these laws. The analytical study and experimental work which constitutes the subject of this paper is one more effort toward the same goal; it is limited to a study of the law of magnetization for flux density in the neighborhood of saturation. Stated symbolically, the subject of this investigation is the equation,

$$B = F\,(H) \qquad (\mathbf{1})$$

and the problem in hand is the determination of the form of the function $F\,(H)$ and its properties. For reasons to be explained later, the form of the problem is slightly modified in the course of the study. (See § 3, equation **4**, and § 9, equation **23**.)

The plan of presentation of results which is followed in this paper is:

Nomenclature and symbols, with illustrative curves. Attention is directed to characteristic peculiarities of curves which occupy an important place in the subsequent argument.

Study of Ewing's conception of intrinsic induction, and of Weber's theory of molecular orientation, as a ground work for formulating a law of magnetization. (§ 3, 4; equations **4**, **6**).

Presentation of Frolich's law as a hypothesis in relation to Weber's theory. (§ 5, equation **7**.)

Study of different forms of Frolich's law, with a view to formulate some crucial equations whereby the validity of Frolich's law can be tested. (§ 5, 6, 7, 20; equations **7**, **9**, **11**, **12**, **17**, **32** and **33**.)

Further study of Weber's theory, as groundwork for equation of progress near saturation. (§ 8, 9; equations **22**, **23**).

Presentation of Frolich's law, as a hypothetic equation of progress. (§ 10, equation **24**.)

Experimental study of a curve of incremental permeability and reluctivity. It will be shown that the form of the observation curves does not support Frolich's law, but that on the contrary, its indications are in favor of Lamont's equation of progress. (§ 11, Fig. 3-1, equation **26**.)

(Supplement, § 20, Fig. 3-3, -4, equations **32**, **33**).

Law of latent induction ($\log \gamma = f - g\,H$) is derived as a corollary to Lamont's equation of progress. (§ 11, equation **29**.) This leads to the equation of magnetization, $B - H = S\,(1 - b\,e^{-aH})$, referred to in the synopsis. (Equation **30-2**.)

Study of saturation value and of $\beta\,H$, $\beta\,\mu$ and $H\,D$ curves for standard sheet steel. A study of these curves shows, first, that the magnetization curve for this material does not follow Frolich's law, and second, that for the part of the curve above $H = 300$, it follows the law $\text{Log}\ \gamma = f - g\,H$. (§ 12, 13, 14.)

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Study of H ρ curve. The apparent straightness of the H ρ curve seems at first sight to support Frolich's law, but a closer study of the curve reveals that this is due to its insensitive character, and proves that it has no evidential value (§ 15, equation **31-2**).

Corroborative evidence from tests on other typical samples (§ 16).

Further corroborative evidence from tests at the Bureau of Standards. (§ 17, Fig. **12-2, -4.**)

Practical application of both laws for purpose of extrapolation beyond the limits of test (§ 18).

Summary of conclusions.

Tables of data and curves.

The scheme of numbering the tables and curves is such that all figures with a common group number refer to tables with the same group number. The sub-numbers have no significance; they are used merely as a convenient mark for subdivision of the group. In view of the difficulties due to the large number of figures necessary to illustrate the various points of the argument, a few curves are selected for publication. Other curves will be available in the form of blue prints, for anyone who desires to study the results farther than they are given in this paper.

Necessary references to all curves, including those that are not published, will be found in the tables. References to published curves only are given in the body of the text, each in its proper place.

2. Nomenclature and Symbols

The following symbols are used in this paper:

B Total induction, or flux density (gausses).

β Intrinsic induction, or flux density (gausses).

H Magnetizing force, (gilberts per cm.: briefly g).

H Spatial induction, (gausses, See par. 3, note 1).

S Saturation value, *i. e.*, limiting value of β.

γ Latent induction, $(= S - \beta)$. (See §4, 8).

μ Intrinsic permeability $(= \beta/H$, not $= B/H)$.

ρ Intrinsic reluctivity $(= H/\beta)$.

D Distribution ratio $(= \beta/\gamma)$.

μ' Transformation rate $(= - d\ \gamma/d\ H$, or $d\ \beta/d\ H)$; also called incremental permeability.

ρ' Incremental reluctivity, $(d\ H/d\ \beta)$.

i_1 First inflection of β μ or H ρ curves.

i_2 Second inflection of β μ or H ρ curves.

a Coefficient of permeability $(= \mu/\gamma)$ when used with reference to Frolich's law in its various forms (equations **7**, **8**, **9**, **12**, **16**, etc.).

a Coefficient of incremental permeability $(= \mu'/\gamma)$ when used with reference to Lamont's equation of progress, and other equations derived from it. (Equation **27**).

σ Coefficient of reluctivity $(= 1/S)$.

α Initial reluctivity $(\alpha = \rho - \sigma H)$. This quantity is also defined as $\alpha = 1/a\,S$. (See equations **10** and **11**).

h Coefficient of magnetic hardness $(h = 1/a)$ when used with reference to Frolich's law (see equation **13**).

Curves are designated by joint use of the variables involved, for example, β H, β μ, H ρ curves; when one of the variables is logarithmic, a comma is inserted, for example H, log γ curve.

For illustration of these symbols see Fig. 1.

NOTES: The symbol H is used in two senses but this ambiguity does not lead to any inconvenience or mis-

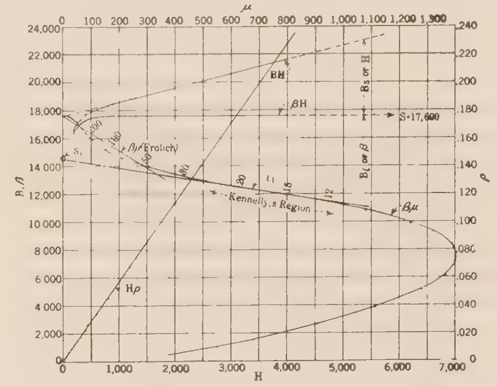

Fig. 1-1—Silicon Steel (Sample No. R437-6)

understanding, as the context is clear in all cases. The same remark applies to the symbol a.

The symbol μ, in the usual sense of B/H, is not used in this paper.

The symbol ρ, in its original sense of H/B, is not used in this paper.

The numerical figures on the β μ curve refer to the

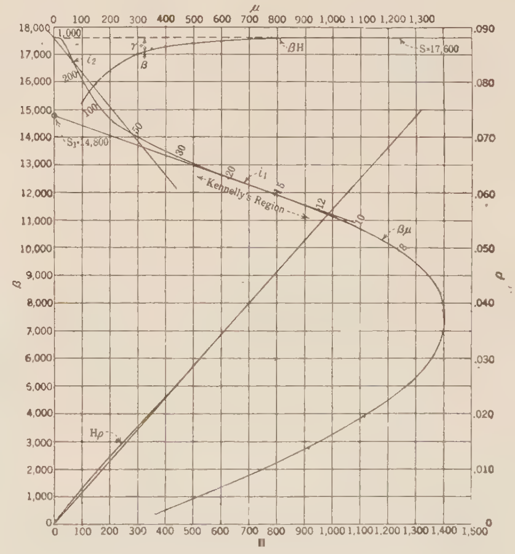

Fig. 1-2—Magnified Section of Fig. 1-1

values of H for the corresponding points. The straight line drawn in relation to the β μ curve is a hypothetic β μ curve for Frolich's law, that is, the β μ curve which would be represented by this straight line if the material followed Frolich's law, within the limits indicated. (Fig. 1-1, -2, -3.)

In relation to the reluctivity curve, the straight line passing through the origin is the ideal reluctivity curve,

that is, a curve for a hypothetical sample of material having the same saturation value as the test sample but having no magnetic hardness, so that the material is supposed to be saturated from the s art. (Fig. 1-1, -2, -3.)

In studying the various curves, the following characteristics should be noted; their significance will be explained later.

(a) The β H curve has the appearance of a hyperbola, asymptotic to the saturation line (Fig. 1-1, -2, -3).

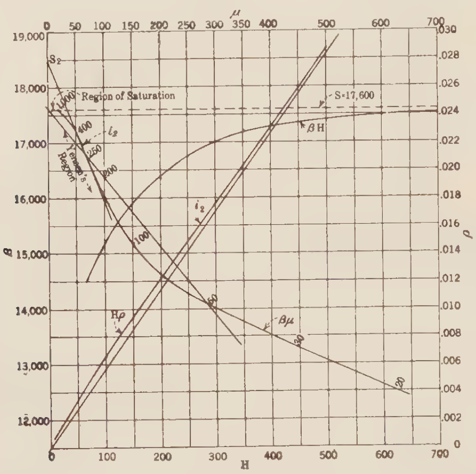

FIG. 1-3—MAGNIFIED SECTION OF FIG. 1-2

It will be shown later that the curve is not truly hyperbolic.

(b) For values of H above a certain limit, (H = 50 approx.), the H ρ curve appears to be almost a perfect straight line (Fig. 1-1, -2, -3). Even below H = 50, the curvature is scarcely noticeable.

(c) For corresponding values of H, the β μ curve is not straight. It contains three straight sections, *viz.*, regions of Kennelly, Yensen, and saturation. (Fig. 1-1, -2, -3.) For further discussion on this point, see §14.

(d) The H D curve is not straight; it has the appearance of an exponential curve. The corresponding logarithmic curve is comparatively straight; in the particular case selected for illustration, the logarithmic curve seems to be made up of two separate straight lines, with a seemingly abrupt bend at H = 370 (Fig. 1-6).

3. EWING'S CONCEPTION OF INTRINSIC INDUCTION

Prior to the year 1890, the various laws of magnetization propounded by several physicists were equations of the form $B = F(H)$ or other equations derived therefrom. In 1890, Prof. Ewing showed that the induction in all ferro-magnetic material could be conceived as made up of two components, each following its own characteristic law.

$$B = B_s + B_i \tag{2}$$

where

$$B_s = F_1(H) = H$$

and

$$B_i = F_2(H)$$

NOTES: B_s is the spatial induction, that is, induction in the space as a magnetic property of the space irrespective of the magnetic character or condition of the material occupying that space. It is supposed to follow the very simple law $B_s = H$. (See Fig. 1-1).

B_i is the intrinsic induction which depends on, and is an undetermined function of, H; it is signified by the symbol β in this paper. (See Fig. 1-1.)

B is the resultant induction in the magnetic material. Using the notation of §2, Ewing's conception is

$$B = H + \beta \tag{3}$$

The problem of determining the law of magnetization is thus reduced to a determination of the equation,

$$\beta = F(H) \tag{4}$$

In view of the fact that Ewing's conception is now generally accepted, it is considered necessary to revise the laws of Lamont, Frolich, etc., and regard them as referring to β, although in their original form they referred to B.

4. WEBER'S THEORY OF MAGNETIZATION, AND CONCEPTION OF LATENT FLUX

According to Weber's theory, as modified by Ewing, all magnetic material consists of molecular magnets; the question regarding the cause of magnetism of the molecules is irrelevant for our present purpose, and is therefore left out of consideration in this paper.

The process of magnetization is merely a process of orientation of the molecules.

In the non-magnetized condition the molecules form a large number of small groups, each group making a small but complete magnetic circuit.

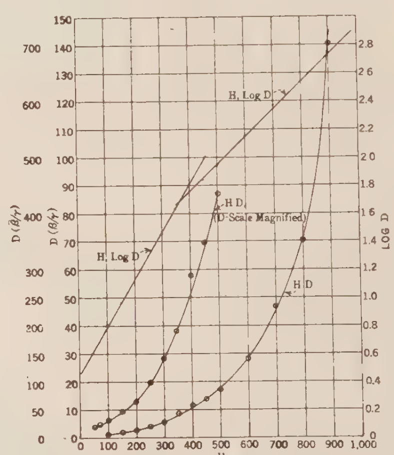

FIG. 1-6—H D AND H LOG D CURVES

The molecules in each group are held in their place by magnetic forces which originate in the molecular magnets of that group as well as of neighboring groups.

When a magnetizing force is applied to the magnetic material, each molecular magnet acting as a compass needle tends to turn around and place itself in a line parallel to the magnetizing force. This tendency is partly opposed by the counteracting magnetic forces of the neighboring molecules.

The function of the magnetizing force is therefore merely to determine the configuration of the molecules. For each configuration there is a certain magnitude of H necessary to produce it.

The total flux of the oriented molecules across any section of the magnet is the manifest flux, and this flux, divided by the area of that cross-section, is the manifest induction; it is represented by the symbol β.

The total flux of the unoriented molecules across the same cross-section is the latent flux; it is made up of two groups of flux lines in opposite directions making an algebraic total of zero lines. The total number of these lines reckoned without consideration of direction is the latent flux, and this flux divided by the sectional area of the whole magnet is the latent induction; it is represented by the symbol γ.

The total intrinsic flux in a magnet across any section is the aggregate of flux lines of all molecules irrespective of the direction of the lines. This is a constant quantity not dependent on the magnetizing force, being determined only by flux in each molecule and by the total number of molecules in the plane of the cross section; it is represented by the symbol S.

The function of the magnetizing force is to establish a

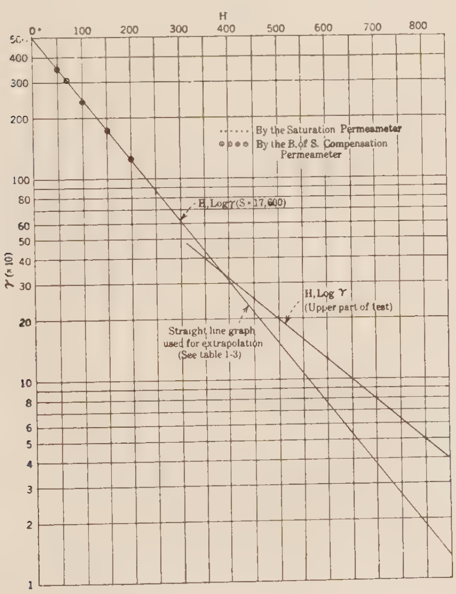

FIG. 1-7—H γ CURVE

configuration of the molecules and therefore the distribution of S into its two components β and γ. (See Fig. 1-2.)

Weber's theory may therefore be stated analytically by the equations,

$$\beta + \gamma = S \tag{5}$$

and

$$\beta / \gamma = F(H) \tag{6}$$

the form of the function H being undetermined for the present.

5. FROLICH'S LAW: HYPOTHETIC EQUATION OF DISTRIBUTION RATIO

We have seen that according to Weber's theory $\beta/\gamma = F(H)$, the form of the function being yet undetermined. If at this point we assume that the distribution ratio is not only a function of H but is directly proportional to H, we arrive at the equation,

$$\beta/\gamma = a\,H \qquad\qquad (7)$$
$$= H/h$$

where $h = 1/a$,

or

$$D = a\,H = H/h \qquad\qquad (7\text{-}2)$$

This equation may be called Frolich's hypothesis be-

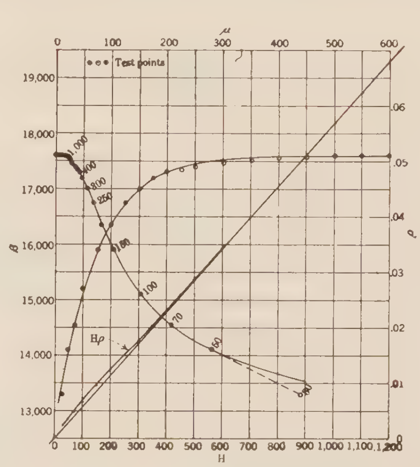

FIG. 1-8—RECONSTRUCTION OF CURVES BY LOGARITHMIC LAW

cause it is implied in Frolich's law. It has not been explicitly stated in this form by Dr. Frolich or by any one else. Substituting for γ its equivalent $S - \beta$, we get

$$\beta/\gamma = a\,H$$
$$\therefore \beta/(S-\beta) = a\,H \qquad\qquad (8)$$
$$\therefore \qquad \beta = S \,.\, a\,H/(1 + a\,H) \qquad\qquad (9)$$
$$= S - S/(1 + a\,H) \qquad\qquad (9\text{-}2)$$

This is Frolich's law (*E. T. Z.*, 1886, p. 164).

Equation (9) can also be expressed as

$$\beta = \frac{H}{\dfrac{1}{a\,S} + \dfrac{H}{S}}$$

$$= \frac{H}{\alpha + \sigma\,H} \qquad\qquad (10)$$

where

$$\alpha = 1/a\,S, \text{ and } \sigma = 1/S.$$

This is another form of Frolich's law (*E. T. Z.*, 1882, p. 71).

From equation (10) we obtain

$$H/\beta = \alpha + \sigma\,H$$

or

$$\rho = \alpha + \sigma\,H \qquad\qquad (11)$$

or

$$\rho = (H + h)/S \qquad \textbf{(11-2)}$$

This equation is known as Kennelly's law. It was formulated first by Prof. Fleming, who derived it as a corollary to Frolich's law, (J. I. E. E. *Trans.*, 1886, p. 569); second by Dr. Kennelly, who derived it independently of Frolich's law, empirically from a study of the published data of Ewing, Rowland and Du Bois, (A. I. E. E. TRANS., 1891, p. 503-517); and third by Dr. Steinmetz, who derived it also as an empirical law from the study of data published by Dr. Corsepious, (*E. T. Z.*, 1892, p. 203).

From equation (**8**) we also obtain directly

$$\beta/H = a\,(S - \beta)$$

or

$$\mu = a\,(S - \beta) \qquad \textbf{(12)}$$

or

$$\mu = \gamma/h \qquad \textbf{(12-2)}$$

This is Bosanquet's law, (*Electrician* 1886, p. 247). Equation (**12**) may also be derived directly from equation (**11**) by purely algebraic process involving no other equations except the defining equations,

$$\mu = \beta/H$$
$$\rho = H/\beta$$
$$\alpha = 1/a\,S$$

and

$$\sigma = 1/S$$

The relation of equation (**12**) to equation (**11**) is not dependent on their relation to equation (**7**) or (**8**) or to any other hypothesis. From this it follows that if any part of the $H\,\rho$ curve is straight, the corresponding part of the $\beta\,\mu$ curve must also be straight.

Again, starting with equation (**9**)

$$\beta = S\,.\,a\,H/(1 + a\,H)$$

and using a symbol $h = \dfrac{1}{a}$ (see equation **7-2**), we get

$$\gamma = S\,h/(H + h) \qquad \textbf{(13)}$$
$$\beta = S\,.\,H/(H + h) \qquad \textbf{(14)}$$
$$= S - S\,h/(H + h) \qquad \textbf{(15)}$$

NOTE: The relation of equations (**7-2**), (**9**), (**11-2**), (**12-2**), (**13**), (**14**), (**16**) and (**17**) can be easily demonstrated geometrically with the help of Fig. 2-1. For example,

$M\,P/P\,N = O\,M/N\,Q$ or $\beta/\gamma = H/h$, equation (**7-2**).

Again $M\,P/O\,S = O\,M/S\,Q$, or $\beta/S = H/(H + h)$, equation (**14**).

Equations (**13**), (**14**) and (**15**) are equations for Frolich's law in its analytical form. They lend themselves easily to computation of β and γ for any value of H. Equation (**15**) is preferred in this paper in the preparation of the several tables. For example, see Table II. The several equations given above lead us to expect that

1. If Frolich's law be true for the entire curve above any value of H, the corresponding parts of the $H\,\rho$, $\beta\,\mu$ and $H\,D$ curves should be straight lines, as the corresponding equations are all of the first degree. (See equations **7-2**, **11** and **12**. Fig. 2-1.)

2. If Frolich's law be true only between certain limits and not true above and below that limit, the $H\,\rho$ and $\beta\,\mu$ curves should be straight between those limits, but the $H\,D$ curve should not be straight even between those limits if the true saturation value determined by measurement be used as a basis of computation, unless the value of S indicated by the straight part of the $H\,\rho$ or $\beta\,\mu$ curve happens to be the true saturation value. No concrete instance of such exceptional coincidence has yet been observed.

3. In no case is it possible to find a particular part of the $H\,\rho$ curve straight unless the corresponding part of the $\beta\,\mu$ curve is also straight.

These three curves, *viz.*, the $\beta\,\mu$, $H\,\rho$ and $H\,D$ curves, are therefore three practical tests whereby the truth of Frolich's law for any part of the $\beta\,H$ curve may be tested; two other practical tests will be described later. (See §6 and 20.)

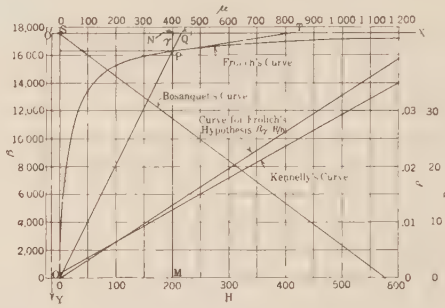

FIG. 2-1—FROLICH'S LAW AND COGNATE CURVES

The $\beta\,H$ curve is an equilateral hyperbola with asymtotes $O'\,X$, $O'\,Y$

$\beta = M\,P$	Then	$\beta/H = S/(H + h)$	Frolich's Law
$\gamma = N\,P$		$\beta/H = \gamma/h$	Bosanquet's Law
$H = O\,M = S\,N$		$H/\beta = (H + h)/S$	Kennelly's Law
$S = O\,S$		$\beta/\gamma = H/h$	Frolich's Hypothesis
$h = O'\,S = N\,Q$		$\beta/S = H/(H + h)$	
$H + h = O'\,N = N\,T = S\,Q$		$d\beta/d\,H = P\,N/N\,T$	
		$= r/(H + h)$	
		$= r^2/S\,.\,h$	Frolich's Equation of Progress

6. FROLICH'S EQUATION OF PROGRESS AND EMERY'S LAW

By differentiation of equation (**12**), we obtain,

$$\mu' = \frac{a}{S}\,(S - \beta)^2 \qquad \textbf{(16)}$$

$$= K\,(S - \beta)^2 \qquad \textbf{(17)}$$
$$= \gamma^2/S\,h$$

where

$$K = a/S = 1/S\,h.$$
$$\therefore \mu = \gamma/H + h) \qquad \textbf{(17-2)}$$

(See equation **13**.)

This is Frolich's equation of progress of magnetization. (*E. T. Z.*, 1886, p. 164.) By reintegration of equation (**16**), we get

$$\beta = S\,(a\,H + c\,S - 1)/(a\,H + c\,S) \qquad \textbf{(18)}$$

or

$$\beta = S - S/(a\,H + c\,S) \qquad \textbf{(19)}$$

where c is an undetermined constant of integration. This is Emery's law. (A. I. E. E. TRANS., 1892, pp. 209, 215.) In equation (**18**) or (**19**), if $c = 1/S$, the equation reduces itself to the form

$$\beta = S \,.\, a\, H/(1 + a\, H) \tag{9}$$

or

$$\beta = S - S/(1 + a\, H) \tag{9-2}$$

This is Frolich's law.

From Emery's law we have,

$$\beta/\gamma = a\, H + c\, S - 1 \tag{20}$$

According to Emery's law the distribution ratio expressed as a function of H is a straight line not passing through the origin except in the particular case where $c\, S - 1 = 0$ in which case Emery's law becomes Frolich's law; in either case it is a straight line. Equation (**16**) is an equation of first degree for μ' and second degree for β. Therefore, if Frolich's law be true, the corresponding curve should be a parabola with the vertex at the point S on the axis of β, and with its directrix parallel to the axis of β.

7. Study of Equations of Distribution Ratio (Equations 7 and 20)

We have seen that Frolich's law in all its forms, and even Emery's law, involves the hypothesis that the distribution ratio is a linear function of H. Such an assumption has no justification either theoretical or empirical. Fig. 1-6 shows the curve for distribution ratio for a selected sample of silicon steel. This curve is certainly not a straight line. On the theoretical side we have against it the negative fact that no reason has yet been given to explain why the ratio β/γ should be a simple linear function of H. It is true that there is nothing inherently absurd in the assumption that the ratio of the components β and γ is proportional to magnetizing force; it does not conflict with Weber's theory, but neither is there anything in Weber's theory to justify or even to suggest that assumption; in fact even the form of the general equation (**6**), that is, $\beta/\gamma = F\,(H)$, does not express the fundamental nature of the phenomenon which would be better expressed by a differential equation of the form,

$$d\,\beta/d\,H = F\,(\beta,\, \gamma)$$

although the final result may be expressed in any convenient form, including the form,

$$\beta/\gamma = F\,(H)$$

NOTE: We have seen that the curve β/γ as a function of H is not straight, but has the appearance of an exponential curve corresponding to the equation $\beta/\gamma = e^{H}$. (See §2 par. d.) If this conjecture be correct, the curve for log β/γ should be a straight line. This expectation is found to be partly justified by Fig. 1-6. This point will be discussed more fully later. (See §13, equation **30-4**.)

8. Equation of Progress According to Weber's Theory

According to Weber's theory, the values of β and γ for any value of magnetizing force depend on the configuration which has been reached under the influence of that force, and which is therefore determined by the condition of equilibrium between the internal and external magnetic forces when that configuration is established. The internal forces are those due to the interaction of the magnetic poles of the molecules, from which it follows that the forces which oppose the change of configuration at any step in the process of magnetization are determined by the configuration itself. According to this conception, the process of magnetization is a progressive process made up of changes of configuration in successive steps, and is, at each step, accompanied by a transformation of a small part of the latent induction $d\,\gamma$ into an equal amount of manifest induction $d\,\beta$, under the influence of the incremental magnetizing force $d\,H$. The fundamental law of magnetization should therefore be an equation of the form,

$$d\,\gamma/d\,H = -\,F\,(\beta,\, \gamma) \tag{21}$$

or

$$d\,\beta/d\,H = F\,(\beta,\, \gamma) \tag{22}$$

Equations (**21**) and (**22**) are identical, being merely the negative and positive aspects respectively of the same transformation process. In formulating this conception, the transformation ratio ($d\,\gamma/d\,H$) is expressed as a function of β and γ, but not as a function of H; this is because, according to the conception under discussion, the transformation of $d\,\gamma$ into $d\,\beta$ is brought about by the operation of the increment $d\,H$, not by the whole magnetizing force H. The function of the magnetizing force H is to establish the corresponding configuration by counteracting the opposing internal forces, and when that configuration has been reached the function is exhausted. Any further change in the value of β and γ is brought about by the incremental component of force $d\,H$, and the magnitude of this component necessary for unit change in γ and β is determined by the component of internal force which it has to oppose and overcome. This component of internal force is the result of, and therefore some mathematical function of, the configuration itself, that is, a function of β and γ; it follows therefore that the rate of transformation $d\,\gamma/d\,H$ must be fundamentally a function of β and γ but not of H. But since β and γ are themselves functions of H, it also follows that $d\,\gamma/d\,H$ is capable of being expressed as a function of H, although such an equation would not be the fundamental equation.

9. Equation of Progress Near the Saturation Limit

We have seen that $d\,\gamma/d\,H$ is a function of β and γ. (See equation **21**.) At this point, we can introduce a further simplification by limiting the problem to the part of the curve near saturation. As saturation approaches, the manifest component of flux β becomes practically constant. The corresponding oriented molecules are now practically in the final stage of orientation; their influence in opposing any change of configuration is

now practically constant irrespective of how great or how small that influence happens to be; this makes the transformation ratio depend on the γ component of S only, which is now practically the only variable in the function.

Thus we have the equation,

$$d\,\gamma/d\,H = -\,F\,(\gamma) \qquad (23)$$

the form of the function $F\,(\gamma)$ being yet undetermined; the determination of the function $F\,(\gamma)$ now becomes the main problem.

10. Study of Frolich's Equation of Progress

At this point we might make some assumption as to the form of the function $F\,(\gamma)$. If we assume $F\,(\gamma) = K\,\gamma^2$, we have

$$d\,\gamma/d\,H = -\,K\,\gamma^2 \qquad (24)$$

or

$$d\,\beta/d\,H = K\,(S - \beta)^2 \qquad (25)$$

This is Frolich's equation of progress (see equation **17**) wherein K represents the ratio of Frolich's constants, a/S, (see §6, equation **16**). The status of Frolich's law depends on the validity of the assumption $d\,\beta/d\,H = \dfrac{a\,(S - \beta)^2}{S}$. On the theoretical side no justification for this assumption has been given by Dr. Frolich or by any one else. On the empirical side, there is no experiment on record to demonstrate that the curve for incremental permeability as a function of β is a parabola such as is represented by the equation in question.

11. Form of Curve for Incremental Permeability and Equation of Latent Induction

In order to ascertain the validity of Frolich's assumption (Equation **16** or **24**), a sample of standard

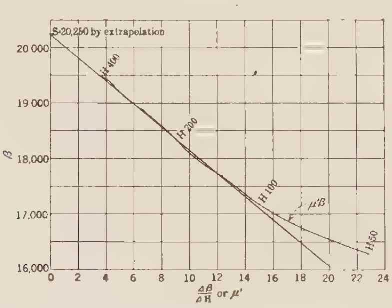

Fig. 3-1—Standard Sheet Steel Ring Curve of Incremental Permeability

steel in the form of a toroid ring was tested by the differential method. For details of test and result of measurement see Table III, Fig. 3. The curve plotted from test has certainly no resemblance to the parabola representing the equation $d\,\beta/d\,H = \dfrac{a\,(S - \beta)^2}{S}$. Incidentally, we observe that the observation curve, though not perfectly straight, is very nearly a straight line for magnetizing forces above $H = 100$, and still more straight above $H = 200$. The test stops at $H = 400$; extrapolation of the curve indicates a saturation value of $S = 20{,}250$. (For true value of S, see next paragraph.) We might therefore follow the

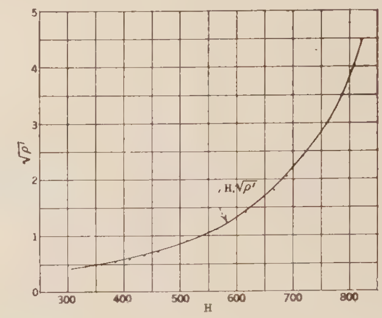

Fig. 3-3—Standard Sheet Steel Ring Curve of Incremental Reluctivity H as a Function of $\sqrt{\rho'}$

suggestion of this experiment and assume that the function $F\,(\gamma)$ in equation (**23**) is $a\,\gamma$.

This leads to the equations

$$d\,\gamma/d\,H = -\,a\,\gamma \qquad (26)$$

or

$$d\,\beta/d\,H = a\,(S - \beta) \qquad (27)$$

This is Lamont's hypothetical equation of progress.

By integrating either of these, we have

$$\log_e \gamma = C - a\,H \qquad (28)$$

where C is an integration constant,

or

$$\log_{10} \gamma = f - g\,H \qquad (29)$$

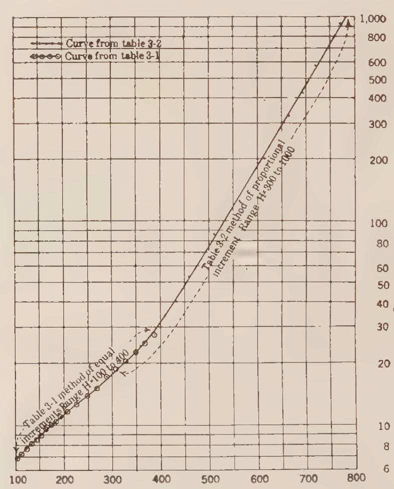

Fig. 3-4—Curve of Incremental Reluctivity H as a Function of Log ρ'

From equation (**28**), we get

$$\beta = S\,(1 - b\,e^{-aH}) \qquad (30)$$

where $b = e^c/S$,

or

$$B - H = S\,(1 - b\,e^{-aH}) \qquad (30\text{-}2)$$

This is the law of magnetization referred to in the synopsis.

Equation (**30**) is the same as Lamont's equation in form, but differs from it in the limitations which are implied in equations (**26**) and (**30**) but not recognized by Lamont, *viz.*, that the equation is true for parts of curve near saturation only (See par. 9). Lamont assumes that the equation is true for all values of H including $H = 0$, which makes $b = 1$; Lamont's equation therefore takes the form,

$$\beta = S\,(1 - e^{-aH}) \qquad (\mathbf{30\text{-}3})$$

This equation has no experimental support.

12. LAW OF MAGNETIZATION FOR STANDARD SHEET STEEL

In order to ascertain the reliability of the extrapolation method based on the assumption $d\,\gamma/d\,H = -\,a\,\gamma$, the ring referred to in the last paragraph was unwound and rewound for higher magnetizing force reaching up to $H = 1000$, if possible. (For details of test and result of measurement, see Table IV, Fig. 4). The sample seems to be saturated at $H = 650$, reaching the saturation value of $S = 20{,}200$, which is in very close agreement with that indicated by extrapolation,

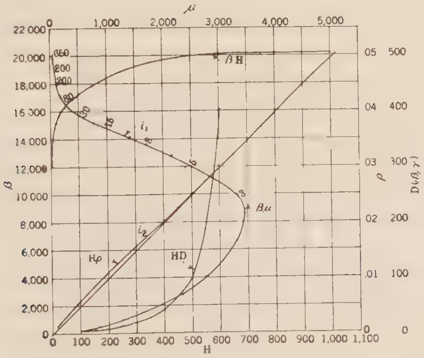

FIG. 4-1—STANDARD SHEET STEEL RING

viz., 20,250 (See Fig. 3). For magnetizing forces above $H = 300$, the observation curve is in very close agreement with the reconstruction curve representing the law, $\log\gamma = f - g\,H$; (see Fig. 4-4); it is not in as good agreement with the law $\beta = S\,a\,H/(1 + a\,H)$. (See Fig. 4-5.)

13. CURVE OF DISTRIBUTION RATIO FOR STANDARD SHEET STEEL

According to the equation (**7**), ($\beta/\gamma = a\,H$), the curve for distribution ratio should have been a straight line. The observation curve is certainly not straight, (Figs. 1-6, 4-1). On the contrary, the curve seems to be exponential, as it ought to be if equation (**30**) represented the true law of magnetization; for,

$$\beta = S\,(1 - b\,e^{-aH}) \qquad (\mathbf{30})$$

Then

$$\gamma = S\,.\,b\,e^{-aH}$$

Then

$$\beta/\gamma = (1 - b\,e^{-aH})/b\,e^{-aH}.$$

$$= \frac{1}{b\,e^{-aH}} - 1$$

$$= \frac{1}{b\,e^{-aH}} \text{ approximately as sat-}$$

uration approaches,
or

$$D = e^{aH}/b \qquad (\mathbf{30\text{-}4})$$

or $\text{Log}_{10} D = p\,H + q$ (making due allowance for change of base). The corresponding observation curve

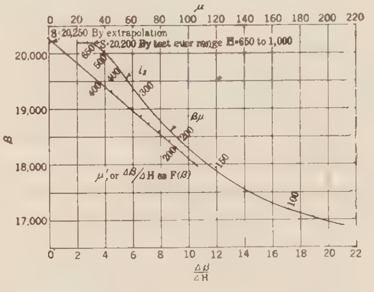

FIG. 4-2—MAGNIFIED SECTION OF $\beta\mu$ CURVE, FIG. 4-1 $\mu'\rho$ CURVE FROM FIG. 3-1 REPRODUCED FOR COMPARISON

is approximately straight, showing that the distribution ratio is not a linear function of the magnetizing force as is required by Frolich's law, but nearly an exponential function as is required by the law of equations (**29**) and (**30**).

14. THE PERMEABILITY AND RELUCTIVITY CURVES

According to Frolich's law, equation (**12**), ($\mu = a\,(S - \beta)$, the $\beta\,\mu$ curve should be a straight line

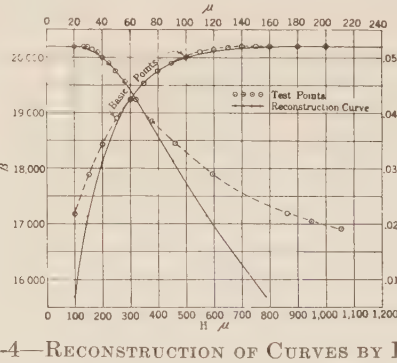

FIG. 4-4—RECONSTRUCTION OF CURVES BY LOG LAW

intersecting the axis of β at the point S. The observation curve does not seem to fulfill this condition, (see Fig. 4-1, -2). For magnetizing forces above $H = 300$, the curve seems to follow very closely the law $\log\gamma = f - g\,H$. The complete $\beta\,\mu$ curve is not straight, but it has three straight regions.

1. First straight region, associated with the first inflection i_1 (Kennelly's region; see Figs. 1-1, 4-1).
2. Second straight region, associated with the second inflection i_2 (Yensen's region; see Figs. 1-3, 4-2).
3. Region of saturation.

The work of Dr. Kennelly was limited mostly to that part of the βH curve which corresponds to the first straight region, (see Fig. 5-2); and the work of Dr. Yensen was limited to the second straight region, (see Fig. 5-1). From the form of the $\beta \mu$ curve it is obvious that Frolich's law should hold true within the corresponding limits of H for each of these regions, but not for the whole curve above the first or even above the second region. The first and second regions can be

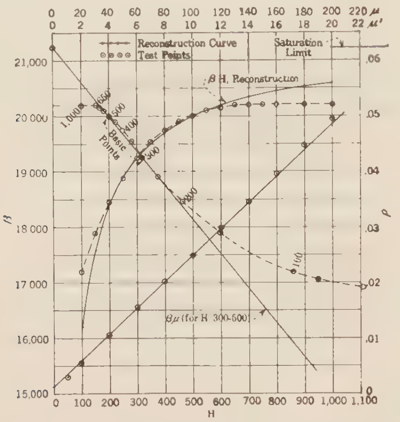

Fig. 4-5—Reconstruction of Curve by Frolich's Law on the Basis of Yensen's Region

represented by the equations, $\mu = a_1 (S_1 - \beta)$, and $\mu = a_2 (S_2 - \beta)$, respectively, (see Figs. 1-1, -3), but it must be remembered that neither S_1 nor S_2 represent necessarily the true saturation value. In all cases observed thus far, S_1 is always less, and S_2 always greater, than S. (See Figs. 1-1, -2, -3; S_1 = 14,800, S_2 = 18,430, S = 17,600.) The curve for reluctivity as a function of H, *i. e.*, $H \rho$ curve, possesses all the characteristics of the $\beta \mu$ curve, but they are not so easily noticeable in the $H \rho$ curve, (see Figs. 1-1, -2; for points i_1 and i_2, see Figs. 1-3, 4-1, -2). The $H \rho$ curve seems to be almost a perfect straight line; in some cases, it seems to resolve itself into two straight lines connected by an apparently abrupt bend; in either case, the straightness is only apparent and misleading.

15. Insensitive Character of Reluctivity ($H \rho$) Curve

It has long been recognized that the reluctivity curves are always almost perfectly straight over a wide range although the corresponding parts of the $\beta \mu$ curves are not straight. (Kennelly: A. I. E. E., 1891, p. 531.) Theoretically, the $\beta \mu$ curve and the $H \rho$ curve are so related that if one of them be straight, the other must be straight also; the straightness of the $H \rho$ curve over a wide range is therefore anomalous, being mathematically impossible when the corresponding part of the $\beta \mu$ curve is not straight. The explanation of the anomaly lies in the insensitive character of the $H \rho$ curve in comparison with the $\beta \mu$ curve. The insensitive character of the $H \rho$ curve is inherent in the form of the function irrespective of the law of reluctivity.

This may be seen from the following analysis:

The insensitiveness of the reluctivity curve may also be demonstrated graphically by choosing for comparison two samples of magnetic material of nearly identical character. (See Table XII-III.) The differences between the two $\beta \mu$ curves are then easily noticeable, but the corresponding $H \rho$ curves are practically indistinguishable except near the upper end of the curves. Fig. 5-1 is a concrete example of insensitivity of the $H \rho$ curve. The data for this curve are taken from an experiment by Dr. Yensen (A. I. E. E. Trans., 1920, p. 821). In the data as originally published, there appears to be a typographical error which becomes manifest in the βH and $\beta \mu$ curves but is scarcely noticeable in the $H \rho$ curve.

16. Magnetization Curves for Magnetic Metals and Binary Ferric Alloys

In view of the importance of the conclusions reached in the foregoing pages, it seemed advisable to extend the experiment to a variety of samples. The following list contains a few samples selected for purpose of demonstration; only toroid ring samples are included in this list.

1. Pure iron, electrolytic vacuum fused and vacuum annealed.
2. Pure nickel, 99.5 per cent nickel.
3. Pure cobalt, percentage not specified.

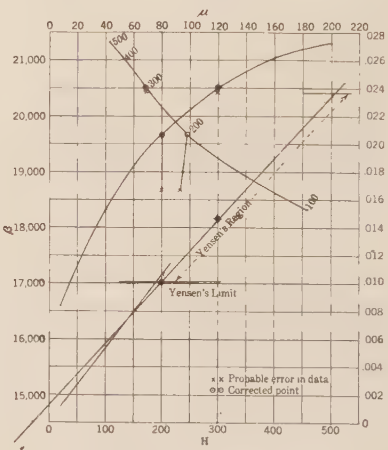

Fig. 5-1—Yensen's Curve for $2\ N\ i$ 204

Note: This sample was used by Mr. J. D. Ball in his well-known experiment: G. E. *Review*, 1916, p. 379.

4. Iron nickel alloy, 72 per cent nickel.
5. Iron cobalt alloy, 20 per cent cobalt.

For details of test and results of measurement see tables and curves in appendix.

A study of the curves shows that:

1. In all cases except cobalt, the samples are saturated well within the limits of test.
2. In all cases the complete $\beta \mu$ curve above the point of maximum permeability is not straight, but has all the peculiarities mentioned in par. 14, *viz.*, the two inflections and the three straight regions. In the case of

cobalt, the curve is incomplete but it demonstrates the first two straight sections.

3. The curve of distribution ratio is not straight as required by Frolich's hypothesis, but has the appearance of an exponential curve.

4. The βH curve by measurement is in closer agreement with the reconstruction curve according to the logarithmic law than with the reconstruction curve by Frolich's law. The same remark applies to the other derived curves, such as the $\beta \mu$ curve.

5. Below the second inflection, the βH curve does not follow the logarithmic law; according to the theory out-

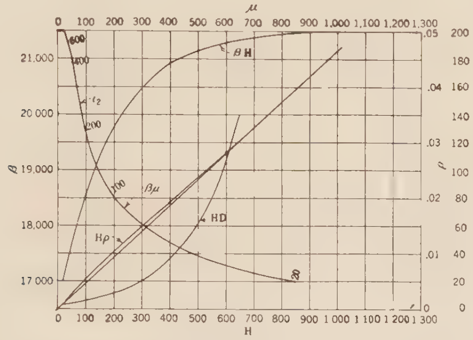

FIG. 12-2—ELECTROLYTIC IRON MAGNIFIED SECTION—TEST BY BUREAU OF STANDARDS

lined above, this disagreement should be expected, for the rate of transformation is no longer capable of being represented by the simpler equation, $d\,\gamma/d\,H = -\,a\,\gamma$, but must be a more complex function involving both β and γ. (See equation **21**.)

By way of further evidence in support of item (4), I may refer once more to Fig. 1, which has been obtained by the saturation permeameter. In this case also the βH curve is in closer agreement with the logarithmic law than with Frolich's law, (Fig. 1-8). Tests by the saturation permeameter run into several hundred samples. It is obviously not practicable to include them all in this paper, and I must therefore limit myself to the bare statement that in all cases the observation curve follows the logarithmic law much more closely than Frolich's law.

17. Corroborative Evidence from Tests at the Bureau of Standards

Further evidence in support of the above findings will be found in the data from tests at the Bureau of Standards (See Table XII, Fig. 12). In this case the material under test was a group of samples of electrolytic iron carefully prepared by Dr. T. D. Yensen. The tests were made at the Bureau of Standards; both the material and the test results are of the highest order of reliability. The curves speak for themselves and need no further explanation.

18. Practical Application of the Law Log $\gamma = f - g\,H$

As a practical application of these conclusions, let us complete by extrapolation the incomplete βH curve for cobalt; the whole procedure is as follows:

19. Summary of Conclusions

We have found that:

1. According to Weber's theory of molecular orientation, the process of magnetization should be expressed fundamentally by an equation of progress of the form

$$d\,\gamma/d\,H = F_1\,(\beta,\ \gamma)$$

and in its ultimate effect by the equation of distribution ratio of the form

$$\beta/\gamma = F_2\,(H)$$

2. For the part of the curve near saturation, the equation of progress should be of the simpler form

$$d\,\gamma/d\,H = -\,F_1\,(\gamma)$$

3. Frolich's law involves the assumption, fundamentally, that

$$d\,\gamma/d\,H = -\,K\,\gamma^2$$

and in ultimate effect that

$$\beta/\gamma = a\,H$$

This assumption has no theoretical justification or empirical support.

4. In the case of a toroid ring of standard sheet steel, it was found that for magnetizing forces $H = 200$ to 400, the progress of magnetization followed, approximately, the equation

$$d\,\beta/d\,H = a\,(S - \beta)$$

5. From the above equation, it follows that as

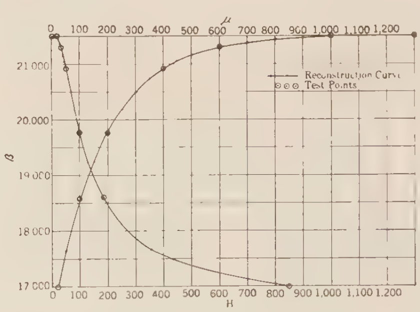

FIG. 12-4 -RECONSTRUCTION OF CURVE BY LOG LAW

saturation approaches, the magnetization should be expected to follow approximately the equation

$$\log\,\gamma = f - g\,H$$

This expectation has been justified by subsequent verification (see next item).

6. For magnetizing forces above the second inflection of the permeability curve, the βH curve follows the law $\log\,\gamma = f - g\,H$ more closely than any other law yet formulated.

7. The part of the $\beta\,\mu$ curve above the point of

maximum permeability is not straight, but it contains three straight regions, *viz.*,

(a) The region of first inflection (Kennelly's region).

(b) The region of second inflection (Yensen's region).

(c) The saturation region.

8. It follows from this observation that a magnetization curve does not follow Frolich's law except in the first two regions mentioned above. The corresponding parts of the βH curve are segments of equilateral hyperbola corresponding to the equations

$$\beta = S_1 a_1 H/(1 + a_1 H)$$

and

$$\beta = S_2 a_2 H/(1 + a_2 H)$$

where S_1 and S_2 are the indicated saturation values corresponding to the two inflection regions. S_1 is always less, and S_2 always greater, than the true saturation values.

9. The part of the $H\,\rho$ curve above the point of minimum reluctivity appears to be very straight. The straightness of the $H\,\rho$ curve has been generally regarded as a conclusive evidence in favor of Frolich's law, but it has now been demonstrated that the straightness of this curve is only a geometric illusion, being caused by the insensitive character of the reluctivity function. The insensitiveness of the $H\,\rho$ curve has been proved analytically and demonstrated graphically. It follows therefore that the straightness of the $H\,\rho$ curve is misleading, and that the curve is therefore not reliable for purpose of drawing any conclusion as to the nature of the law of magnetization or for extrapolation of the $\beta\,H$ curve. The $\beta\,\mu$ curve is a more reliable criterion, and the curvature of a $\beta\,\mu$ curve between any limits demonstrates conclusively the unreliability of Frolich's law for the corresponding range of the $\beta\,H$ curve.

20. Incremental Reluctivity (Supplement)

In paragraph 11, reference is made to an experiment for determination of the incremental permeability $d\beta/dH$ as a function of β. The test stops at $H = 400$; all attempts to extend the test to $H = 1000$ have been unsuccessful. By slightly modifying the test procedure, it has become possible to determine the curve for ρ' or $dH/d\beta$ as a function of H for a range of $H = 400$ to 800. Differentiation of equations (**9**) and (**29**) leads respectively to equations of form

$$\sqrt{\rho'} = H + q, \text{ for Frolich's law} \quad (32)$$

$$\log \rho' = H + q, \text{ for logarithmic law} \quad (33)$$

From these equations it follows that for any range of H,

(a) If Frolich's law be true, the curve H, $\sqrt{\rho'}$ should be straight,

(b) If the law $\log \gamma = f - g\,H$ be true, the curve $H \log \rho'$ should be straight.

Figs. 3-3 and 3-4 represent graphically the result of a test and demonstrate that for the range $H = 400$ to 800, the H, $\sqrt{\rho'}$ curve is not straight, and that the $H \log \rho$ curve is straight, proving thereby that near saturation the $\beta\,H$ curve follows the law $\log \gamma = f - g\,H$ far more closely than Frolich's law. For further details see complete pamphlet form.

TABLE I

4 per cent Silicon Steel: Sample No. R-437-6 (Ref. G. L. 39705-39, -41)

Note: This is a very unusual sample selected for purpose of illustration only because it combines in a single sample all the characteristic peculiarities that call for a demonstration. The sample is not a representative of the grade of steel to which it nominally belongs. Tests above H-200 are made by Saturation Permeameter and below $H = 200$ by the B of S. method.

Table 1-1; test by the Saturation Permeameter
(Not reliable below $H = 1000$)

H	β	B	μ (β/H)	ρ (H/β)	γ ($S = 17600$)	D (β/γ)	Log D
4000	17,600	21,600	4.40	0.2273			
3000	17,600	20,600	5.87	0.1705			
2500	17,600	20,100	7.04	0.1421			
2000	17,600	19,600	8.80	0.1136			
1500	17,600	19,100	11.73	0.0852			
1300	17,600	18,900	13.54	0.0739			
1200	17,600	18,800	14.66	0.0682			
1100	17,600	18,700	16.00	0.0625			
1000	17,600	18,600	17.60	0.0568	0		
900	17,575	18,475	19.53	0.0512	25	702.	2.896
800	17,550	18,350	21.94	0.0456	50	352.	0.546
700	17,525	18,225	25.03	0.03995	75	234.	0.370
600	17,475	18,075	29.12	0.03434	125	139.7	0.145
500	17,400	17,900	34.8	0.02874	200	87.0	1.940
450	17,350	17,800	38.60	0.02595	250	69.4	0.842
400	17,300	17,700	43.25	0.02312	300	57.7	0.761
350	17,200	17,550	49.15	0.02035	400	43.0	0.633
300	17,000	17,300	56.66	0.01765	600	28.3	0.452
250	16,750	17,000	67.00	0.01493	850	19.7	0.294
200	16,350	16,550	81.75	0.01224	1250		
150	15,800	15,950	105.30	0.00949	1800		
100	15,100	15,200	151.0	0.00662	2500		
50	13,900	13,950	278.0	0.00360	3700		

TABLE I—(*Continued*)

Table 1-3: Reconstruction of $\beta\,H$ and $\beta\,\mu$ curves according to the law $\log \gamma = f - g\,H$

Note: The values of γ for required values of H are read from the graph $\gamma\,H$ (Fig. 1-7), for range of H 50 to 400, and by extrapolation up to H 1200. The value of S taken from test, (Table 1-1).

H	γ	S	β	μ	ρ
30	4080	17,600	13,520	450.7	0.00222
50	3500		14,100	282.0	0.003548
70	3050		14,550	208.0	0.00481
100	2480		15,120	151.2	0.00662
150	1740		15,860	105.7	0.00946
200	1220		16,380	81.9	0.01221
250	870		16,730	66.9	0.01495
300	600		17,000	56.7	0.01764
350	425		17,175	49.1	0.02038
400	300		17,300	43.3	0.02310
450	210		17,390	38.7	0.02585
500	150		17,450	34.9	0.02866
600	70		17,530	29.2	0.03425
700	35		17,565	25.1	0.03984
800	20		17,580	21.9	0.04569
900	10		17,590	19.5	0.0513
1000	0		17,600	17.6	0.0568
1100	0		17,600	16.0	0.0625
1200	0		17,600	14.7	0.06805

TABLE II

Hypothetic curve for Frolich's law and cognate equations

$$\beta = S - \gamma = S - S\,h/(H + h) \text{ Frolich's law} \qquad \text{(equation 15)}$$
$$\mu = S/(H + h) : \rho = (H + h)/S;$$
$$D = H/h = a\,H$$
$$d\,\beta/d\,H = \gamma/(H + h)$$

Note: In the following computations, the value of S is taken from Table 1; the value of h is so selected as to give for $H = 200$ the same value of β as in Table 1.

(1) Determination of constants.

H	β	S	γ	μ	a	h	$S\,.\,h$
200	16,350	17,600	1250	81.75	.0654	15.29	269,000

(2) Computation of β and other cognate quantities.

H	$H + h$	$S\,.\,h$	γ $(S\,h/H + h)$	S	β	μ	ρ	D (β/γ)	$d\,\beta/d\,H$ $=(\gamma/(H + h)$
0	15.3	26,900	17,600	17,600		1150.	0.000869	0.	-
10	25.3		10,630		6,970	697.	0.001435	0.656	420
25	40.3		6680		10,920	437.	0.002290	1.635	166.
50	65.3		4120		13,480	270.	0.00371	3.27	63.1
100	115.3		2330		15,270	152.7	0.00655	6.54	20.2
150	165.3		1630		15,970	106.5	0.00939	9.82	9.87
200	215.3		1250		16,350	81.75	0.01225	13.08	5.81
250	265.3		1015		16,585	66.3	0.01508	16.35	3.90
300	315.3		855		16,745	55.8	0.01792	19.63	2.71
400	415.3		650		16,950	42.4	0.02360	26.17	1.565
500	515.3		520		17,080	34.15	0.02920	32.7	1.010
600	615.3		440		17,160	28.6	0.03500	39.25	0.715
700	715.3		375		17,225	24.6	0.04065	45.80	0.526
800	815.3		330		17,270	21.58	0.04635	52.34	0.405
900	915.3		295		17,305	19.23	0.05200	58.9	0.322
1000	1015.3		265		17,335	17.33	0.05770	65.4	0.261

TABLE III

Curve for transformation ratio for standard steel for range $H = 50$ to 400

Method of Test

1. Material: Several rings were punched from a single sheet of standard sheet steel .014 in. From these punchings several rings were made of the same weight, and similarly wound for preliminary test. Two rings were selected having as nearly as possible the same magnetization curve.

2. Windings: The two selected rings were now wound for the differential test; the potential coils were wound next to the iron and were of about 500 turns of fine wire uniformly wound, each ring having the same number of turns. The magnetizing coil was made of a cable of twenty conductors, connected in series, with a tap at each joint. This scheme of winding permits a change of magnetizing value from any predetermined value to higher values in small and definite equal steps.

3. Scheme of wiring: The two magnetizing coils of the two rings were connected in series; the two potential coils were also connected in series. In all respects the scheme of wiring was the same as the usual scheme for tests on toroids. Two dial switches were provided for control of number of windings. One of the rings was used for measurement and the other for compensation. The potential coil of the compensating ring was provided with a supplementary potential coil of few turns and a fractionizing shunt for exact adjustment of the compensating interlinkage. (For wiring diagram, See Fig. 3-0.)

4. Test procedure for magnetization curve: The magnetization coils of the compensating ring and the test ring are tested alone according to the usual procedure. The galvanometer is calibrated to read 100 gausses per millimeter. Assuming that an error in reading the galvanometer cannot exceed half millimeter, it follows that the relative error does not exceed 50 gausses.

5. Test procedure for differential test: The galvanometer is calibrated to read a flux density of one gauss per millimeter of deflection. The dial switches of both rings are set at 10 each; the magnetizing current is adjusted to give $H = 50$, 100 or 200. On reversing the magnetizing current, there should be no deflection, that is, if the two rings are exactly alike; but as there is always a slight difference, a small deflection is produced in all cases, which can be eliminated by a careful adjustment of the supplementary coil and fractionizing shunt. The dial switch of the test coil is now set at No. 11. On reversing the current, a deflection is produced which represents the increment of flux density in the test ring. Other details of test procedure are too obvious to need explanation.

6. Limits of error: The relative error of any individual point in relation to the whole curve does not exceed 0.5 gauss (corresponding to half millimeter of deflection) and is probably much less for small deflection, which is capable of being read correctly to $^1/_5$ of a millimeter. The whole curve may, however, be in error by any amount not exceeding 50 gausses.

In interpreting the curve, it is permissible to assume the curve to be straight enough for extrapolation, and yet the error in the indicated value of S may be as high as 50 gausses, even though the plotted curve were strictly a straight line.

Note: The original measurements were made in terms of H and apparent B; the true value of B was computed by making correction for space factor.

TABLE III—(*Continued*)

Ring, standard sheet steel 0.014 in.
Diameter 3.5 in., 2.7 in.; mean diameter 3.1 in. = 7.885 cm.
Sectional area 1.245 sq. cm.
Table 3-1: test for incremental permeability

H_t	$H\,a$	$\Delta\,H$	β mean	$\Delta\,\beta/\Delta\,H$
400	380	20	19491.5	3.61
380	360	"	19419.0	4.01
360	340	"	19335.5	4.41
340	320	"	19235.5	4.86
320	300	"	19130.5	5.26
300	280	"	19015.5	5.81
280	260	"	18888.0	6.61
260	240	"	18752.5	7.16
240	220	"	18602.0	7.86
220	200	"	18442.0	8.61
200	190	10	18316.0	9.06
190	180	"	18223.5	9.56
180	170	"	18125.5	9.96
170	160	"	18020.5	10.36
160	150	"	17913.0	11.16
150	140	"	17798.0	11.76
140	130	"	17678.0	12.36
130	120	"	17555.0	13.01
120	110	"	17425.0	13.66
110	100	"	17287.5	14.46
100	95	5	17170.0	15.06
95	90	"	17084.0	15.66
90	85	"	16997.0	16.26
85	80	"	16906.0	16.86
80	75	"	16810.0	17.66
75	70	"	16709.0	18.26
70	65	"	16622.0	19.26
65	60	"	16516.0	20.26
60	55	"	16387.0	21.26
55	50	"	16271.0	22.86

$S = 20250$ by extrapolation. (see Fig. 3-1)

TABLE III-II

Curve for Incremental Reluctivity for Standard Steel for Range H = 300 to 1000 g

This test is similar to that of test table 3-1, except that the increment ΔH is in each case one-twentieth part of H. The magnetizing coil of the test ring was made up of two parts of 700 turns, and 35 turns; the first section alone produces the magnetizing force H_1, and the two sections produce the force H_2. The compensating ring has the magnetizing coil of 700 turns, which also gives the magnetizing force H_1. The potential coils are connected as in test 3-1, giving the value ΔB. Each ring is also equipped with a compensative bakelite ring (see table 4-1) which gives the result in terms of $\Delta \beta$ instead of ΔB. The values ρ', log ρ' and $\sqrt{\rho'}$ are obtained by computation.

TABLE III-II—(*Continued*)

Ring same as in Table 3-1
Windings same as in Table 4
Scheme of wiring same as in Fig. 3-0

H_1	H_2	H mean	ΔH	$\Delta \beta$	μ'	ρ'	$\sqrt{\rho'}$
300	315.	307.5	15.	80	5.33	0.1785	0.433
325	341.3	333.1	16.25	79	4.62	0.2055	0.453
350	367.5	359.	17.5	71	4.057	0.2464	0.4967
375	393.7	384.	18.75	67	3.555	0.2813	0.5302
400	420.	410.	20.	59	2.951	0.3422	0.582
425	447.	435.5	21.25	53	2.494	0.4010	0.6334
450	473.	461.	22.5	42	1.867	0.536	0.7322
500	525.	512.5	25.	31	1.240	0.8064	0.898
550	578.	564.	27.5	22	0.800	1.250	1.117
600	630.	615.	30.	15	0.500	2.00	1.414
650	683.	666.	32.5	10	0.3077	3.25	1.802
675	709.	689.	33.75	8	0.237	4.22	2.055
700	735.	718.	35.	6	0.1714	5.834	2.413
750	788.	768.	37.5	4	0.1066	9.38	3.060
800	840.	820.	40.	2	0.0500	20.0	4.470
850	893.	871.	42.5	0	0	inf.	inf.
900	946.	922.	45.	0	0	"	"
950	998.	974.	47.5	0	0	"	"
1000	1050.	1025.	50.	0	0	"	"

Notes:

$H_2 = H_1 \times 1.05$
H mean $= H_1 \times 1.025$
$\Delta H = H_1 \times .05$
$\mu' = \Delta \beta / \Delta H$
$\rho' = \Delta H / \Delta \beta$

TABLE III-II—(*Continued*)

Test data in Table 3-1; further computation to determine relation of ρ' to H

H	$H\,a$	ΔH	$\Delta \beta / \Delta H$	ρ' ($= \Delta H / \Delta \rho$)	H Mean	$\sqrt{\rho'}$
400	380	20	3.61	0.277	390	0.516
380	360	"	4.01	0.2493	370	0.499
360	340	"	4.41	0.2268	350	0.4765
340	320	"	4.86	0.2059	330	0.454
320	300	"	5.26	0.1890	310	0.435
300	280	"	5.81	0.1721	290	0.415
280	260	"	6.61	0.1513	270	0.389
260	240	"	7.16	0.1396	250	0.3735
240	220	"	7.86	0.1272	230	0.357
220	200	"	8.61	0.1162	210	0.341
200	190	10	9.06	0.1104	195	0.332
190	180	"	9.56	0.1046	185	0.3235
180	170	"	9.96	0.1004	175	0.317
170	160	"	10.36	0.0964	165	0.3105
160	150	"	11.16	0.0896	155	0.2995
150	140	"	11.76	0.0850	145	0.2915
140	130	"	12.36	0.0809	135	0.2845
130	120	"	13.01	0.0768	125	0.277
120	110	"	13.66	0.0732	115	0.271
110	100	"	14.46	0.0691	105	0.263
100	95	5	15.06			
95	90	"	15.66			
90	85	"	16.26			
85	80	"	16.86			
80	75	"	17.66			
75	70	"	18.26			
70	65	"	19.26			
65	60	"	20.26			
60	55	"	21.26			
55	50	"	22.86			

S = 20,250 by extrapolation (see Fig. 3)

TABLE IV

Magnetization Curve for Standard Steel

The ring used for this test is the same as the test ring in Table 3, Fig. 3. The ring was unwound, and rewound with heavier wire to obtain a magnetizing force of H = 1000. In order to eliminate space factor error a compensative ring of bakelite of the same size as the test ring, and wound with the same number of turns of same size wire, was used as a companion ring. The two rings were then treated as a single ring and wound with a common magnetizing coil. During test, the two potential coils of the test ring and the compensative ring are connected in opposition; this arrangement compensates for the entire spatial flux inside of the potential coil of the test ring, and therefore serves the double purpose (1) of eliminating the space factor error and (2) of deducting the spatial flux in the magnetic material. With this arrangement, the galvanometer deflections indicate directly the intrinsic flux density. In testing for saturation value, this method of compensation has the further advantage that the measurement of β is not affected by errors in measurement of the magnetizing current; the adjustment of the current need not be accurate; this permits rapidity of measurement and prevents excessive heating. Without this facility, measurement of saturation value in toroid rings would have been impracticable except in the case of permalloy and other similar material of low magnetic hardness. The following is the result of the test:

TABLE IV—(*Continued*)

Ring Standard Sheet Steel
(Same ring as in Table 3)
Table 4-1: Test Data

H	β	μ	ρ	γ	D ($= \beta/\gamma$)
1000	20,200	20.2	0.0495	0	
900	20,200	22.4	0.04465	0	
800	20,200	25.3	0.0395	0	
750	20,200	26.9	0.03715	0	
700	20,200	28.9	0.03465	0	
650	20,200	31.1	0.03215	0	
600	20,150	33.1	0.02980	50	403
550	20,100	36.5	0.02748	100	201
500	20,000	40.0	0.02500	200	100
450	19,900	44.2	0.02260	300	66.3
400	19,750	49.4	0.02025	450	43.9
350	19,550	55.8	0.01767	650	30.05
300	19,250	64.2	0.01558	950	20.25
250	18,900	75.6	0.01323	1300	14.52
200	18,450	92.3	0.01084	1750	10.55
150	17,900	119.4	0.00838	2300	7.78
100	17,200	172.0	0.00581	3000	5.74
90	17,050	189.5	0.00528	3150	
80	16,900	211.0	0.00474	3300	
60	16,500	275.0	0.00364	3700	
50	16,300	326.0	0.00307	3900	
30	15,700	523.0	0.00191	4500	
20	15,200	760.0	0.001315		
15	14,800	986.0	0.001013		
10	14,200	1420.0	0.000704		
8	13,700	1712.0	0.000584		
6	12,900	2150.0	0.000465		
5	12,000	2400.0	0.0004165		
4	11,250	2817.0	0.0003555		
3	9900	3300.0	0.0003030		
2.5	8600	3440.0	0.0002905		
2.0	6600	3300.0	0.0003030		
1.5	4100	2735.0	0.000367		
1.2	2800	2335.0	0.000429		
1.0	1600	1600.0	0.000625		
0.8	1000	1250.0	0.000800		
0.6	500	833.0	0.001200		

TABLE IV—(*Continued*)

Table 4-2: Reconstruction curve according to Frolich s law on the basis of two points $H = 300$ & 500, (*i. e.* Yensen's region approximate)

(1) Determination of constants S and h.

H	β	μ	$\Delta\mu$	$\Delta\beta$	a	h	$(\gamma = h\,\mu))$	S	$S\,h$	$(\alpha = h/S)$
500	2000	40	24.17	750	.03224	31	1240	21,240	659,000	.00146
300	19,250	64.17					1990	21.240		

(2) Reconstruction of curve.

H	$H + h$	$S\,.\,h$	$\gamma = S\,h/(H + h)$	S	β	μ	ρ	$d\,\beta/d\,H = \gamma/(H + h)$
0	31							
50	81	65,900	8140	21,240	13,100			101.6
100	131		5040		16,200	162	0.00617	38.5
150	181		3640		17,600			29.1
200	231		2860		18,380			12.37
250	281		2350		18,890			8.37
300	331		1990		19,250			6.01
350	381		1730		19,510			4.54
400	431		1530		19,710			3.55
450	481		1370		19,870			2.85
500	531		1240		20,000			2.335
600	631		1045		20,195			1.66
700	731		900		20,340			1.232
800	831		790		20,450			0.951
900	931		710		20,530			0.762
1000	1031		640		20,600	20.6	0.04855	0.620
1200	1230		535		20,705			0.435
1500	1530		430		20,810			0.281
2000	2031		325		20,915			0.161
3000	3030		220		21,020			0.0703
4000	4040		165		21,075			0.0402

TABLE IV—(*Continued*)

Table 4-3: Reconstruction of curve according to Frolich's law with constants selected for agreement at $H = 200$, and infinity

(1) Determination of constants.

H	β	S	γ	μ	h	$S\,h$
200	18,450	20,200	1750	92.25	18.97	383,000

(2) Determination of β and cognate quantities.

H	$H + h$	$S\,h$	γ	β $(S = 20{,}200)$	μ	ρ	$d\,\beta/d\,H$ $\gamma/(H + h)$
0	18.97	38,300	20,200	0	1064	0.000939	1063
50	69.		5525	14,675	293.	0.00342	86.8
100	119.		3215	16,985	169.7	0.00589	27.0
150	169.		2265	17,935	119.6	0.00836	13.4
200	219.		1750	18,450	92.25	0.01085	7.99
250	269.		1425	18,775	75.1	0.01333	5.30
300	319.		1200	19,000	63.3	0.01579	3.76
350	369.		1037	19,165	54.8	0.01827	2.81
400	419.		914	19,285	48.2	0.02074	2.18
500	519.		728	19,470	38.9	0.02570	1.42
600	619.		619	19,580	32.6	0.03060	1.00
700	719.		533	19,665	28.1	0.03560	.742
800	819.		468	19,730	24.7	0.04050	.571
900	919.		417	19,785	22.0	0.04550	.454
1000	1019.		376	19,825	19.8	0.0504	.369
1200	1219.		314	19,885			.258
1500	1519.		252	19,950			.166
2000	2020.		190	20,010			
3000	3020.		120	20,070			
5000	5020.		74	20,125			

TABLE IV—(*Continued*)

Table 4-4: Reconstruction curve according to equation

$$\text{Log}\,\gamma = f - g\,H$$

On the basis of agreement for $H = 300$, 500 and infinity

(1) Determination of constants f and g

H	H	β	S	γ	Log γ	Δ Log γ	g	$g\,H$	f
300	200	19,250	20,200	950	2.9775	.6765	.003383	1.0149	3.9924
500		20,000		200	2.3010			1.6915	3.9925

(2) Determination of β

H	g	$g\,H$	f	Log γ	γ	S	β	μ	ρ
100	.003383	0.3383	3.9924	3.654	4510	20,200	15,690	156.9	.00637
150		0.507		3.485	3055		17,145	114.3	.00874
200		0.676		3.316	2070		18,130	90.7	.01103
250		0.846		3.146	1400		18,800	75.2	.01331
300		1.015		2.977	950		19,250	64.2	.01558
350		1.185		2.807	640		19,560	55.9	.01790
400		1.354		2.638	435		19,765	49.4	.02024
450		1.527		2.465	290		19,910	44.25	.02260
500		1.692		2.300	200		20,000	40.0	.02500
550		1.862		2.130	135		20,065	36.5	.02740
600		2.031		1.961	90		20,110	33.5	.02985
650		2.200		1.792	60		20,140	31.0	.03228
700		2.370		1.622	40		20,160	28.8	.03478
750		2.540		1.452	30		20,170	26.9	.03720
800		2.705		1.287	20		20,180	25.2	.03965
900		3.047		0.945	10		20,190	22.4	.04460
1000		3.382		0.610	0		20,200	20.20	.04950
1200		4.060		-1.830	0		20,200	16.8	.0594
inf.							20,200	0	

TABLE V

Insensitiveness of Reluctivity Curve

Table 5-1: Dr. Yensen's Experiment: A. I. E. E., 1920, p. 821

H	β	μ	ρ	
20	16,600	830	0.0012	
100	18,330	183.3	0.0055	
200	18,670	93.35	0.0107	Error in β, probably typographic
300	20,430	68.1	0.0147	Error in β, probably observational
400	21,030	52.6	0.0190	
500	21.310	42.6	0.0235	
200	19,670	98.35	0.01016	Corrected by guess
300	20,500	68.33	0.01463	Corrected by reference to βH curve

Table 5-2: Dr. Kennelly's Curve; A. I. E. E., 1891, p. 509

B	μ ($=B/H$)	H	β	ρ	μ (β/H)	
0	40					
100	50	2.	98	0.0204	49	
420	100	4.2	416	0 01010	99	
720	150	4.8	715	0.006712	149	
1100	200	5.5	1095	0.005028	199	
1500	225	6.6	1493	0.004465	224	
2080	200	10.4	2070	0.005025	199	
2500	150	16.66	2483	0.006708	149	
2960	100	29.6	2930	0.01010	99	
3500	70	50.0	3450	0.01450	69	
3920	50	78.4	3482	0.02040	49	
4500	32	146.0	4354	0.03353	29.8	H, β, ρ, and β/H incorrect
5000	22	227.0	4773	0.04756	21	
4500	32	140.6	4360	0.03225	31	H, β, ρ, and β/H corrected

TABLE VI

Electrolytic Iron: Sample *E-B*

Table 6-1: Test for β H Curve

Method of test same as in Table 4

H	β	μ	ρ	γ	D ($=\beta/\gamma$)	log D
1160	21,000	18.1	0.0552	0		
1000	21,000	21.1	0.0476	0		
900	21,000	23.3	0.0429	0		
850	21,000	24.7	0.0405	0		
800	21,000	26.3	0.0381	0		
750	20,980	28.0	0.03575	20	1050	3.021
700	20,950	30.0	0.0334	30	700	2.845
650	20,900	32.2	0.0311	100	209	2.320
600	20,850	34.7	0.0288	150	139	2.143
550	20,780	37.8	0.0265	220	95	1.978
500	20,650	41.3	0.0242	350	59	1.771
450	20,500	45.6	0.02195	500	41	1.613
400	20,300	50.7	0.0197	700	29	1.462
350	20,000	57.2	0.0175	1000	20	1.301
300	19,700	67.7	0.01525	1300	15.15	1.180
250	19,300	77.2	0.01295	1700	11.35	1.055
200	18,800	94.2	0.01065	2200	8.5	0.930
150	18,300	122.0	0.00820	2700	6.8	0.832
100	17,500	175.0	0.00572	3500	5.0	0.698
50	16,650	333.0	0.00300	4350	3.84	0.585
20	15,900	795.0	0.001258	5100	3.12	0.495
10	15,400	1540.0	0.000649	5600	2.75	0.440
3	14,250	4750.0	0.000211			
1.0	12,500	12500.0	0.0000800			
0.70	11,500	16400.0	0.0000608			
0.60	10,650	17750.0	0.0000563			
0.55	10,000	18200.0	0.0000550			
0.50	9250	18500.0	0.0000541			
0.45	8300	18450.0	0.0000542			
0.40	6950	17400.0	0.0000575			
0.35	5500	15700 0	0.0000636			
0.30	3800	12650.0	0.0000789			
0.25	2550	10200.0	0.0000980			
0.20	1450	7250.0	0.000138			

TABLE VI—(*Continued*)

Table 6-2: Reconstruction of curve (Table 6-1) by the law $\log \gamma = f - g H$

Note: The values of γ are read from the straight line graph of Fig. 6-3.

H	γ	S	β	μ
50	7800	21,000	13,200	264
100	5500		15,500	155
150	3900		17,100	114
200	2750		18,250	91.25
250	1920		19,180	76.7
300	1350		19,650	65.5
350	960		20,040	57.3
400	680		20,320	50.8
450	480		20,520	45.6
500	340		20,660	41.3
550	240		20,760	37.7
600	170		20,830	34.7
650	120		20,880	32.1
700	85		20,915	29.9
750	60		20,940	27.9
800	40		20,960	26.2
850	30		20,970	24.7
900	20		20,980	23.3
1000	10		20,990	21.0
1100	0		21,000	19.1
1200	0		21,000	

TABLE VII

Nickel Pure: 99.5 per cent Nickel: Ring No. *N-D*

Test 7-1: test for β H curve

H	β	μ	ρ	γ	D (β/γ)
375	5810	15.5	0.0645		
270	5810	21.5	0.0465		
240	5810	24.2	0.0413		
210	5790	27.6	0.03625	20	289.5
180	5750	32.0	0.03122	60	95.8
150	5700	38.0	0.02631	110	51.8
120	5650	47.0	0.02129	160	35.3
105	5600	53.3	0.01875	210	26.68
90	5550	61.6	0.01625	260	21.34
75	5475	73.0	0.01370	325	16.85
60	5350	89.2	0.01121	460	11.63
45	5200	115.5	0.00866	610	8.52
30	5000	166.8	0.00600	810	6.17
15	4600	306.5	0.00326	1210	3.80
7.5	4100	547.0	0.00183	1710	2.41
6.0	3900	650.0	0.00154	1910	2.04
4.5	3600	800.0	0.00125	2210	1.63
3.0	3050	1015.0	0.000986	2760	1.11
2.5	2750	1100.0	0.000910		
2.0	2400	1200.0	0.000833		
1.5	1900	1267.0	0.000790		
1.0	1200	1200.0	0.000833		
.8	850	1060.0	0.000944		
.6	450	750.0	0.001333		
.4	225	560.0	0.001785		
.2	100	500.0	0.002000		

TABLE VII—(*Continued*)

Table 7-2: Reconstruction of curve (Table 7-1) by the law $\log \gamma = f - g H$

Note: Values of γ are read from the straight line graph of Fig. 7-3.

H	γ	S	β	μ
20	860	5810	4950	247.5
40	620		5190	129.6
60	440		5370	89.5
80	320		5490	68.8
100	230		5580	55.8
120	160		5650	47.1
140	120		5690	40.6
160	80		5730	35.8
180	60		5750	31.9
200	45		5765	28.8
220	30		5780	26.2
240	20		5790	24.1
260	15		5795	22.3
280	10		5800	20.7
300	0		5810	19.35
320	0		5810	18.15
340	0		5810	17.10
360	0		5810	16.15
380	0		5810	15.3
400	0		5810	14.5

TABLE VIII

Cobalt Pure: (Percentage composition not specified. This ring is the same that was used by Mr. Ball in his well-known experiment published in G. E. *Review*, 1916, p. 379)

H	β	μ	ρ	
1600	13,000	8.13	0.1232	
1400	12,600	9.00	0.1111	
1200	12,100	10.08	0.0992	
1000	11,600	11.60	0.0862	
800	10,950	13.70	0.0730	
700	10,550	15.07	0.0664	
600	10,200	17.00	0.0588	
500	9700	19.40	0.0516	
400	9050	22.63	0.0442	
360	8800	24.45	0.0409	
320	8500	26.55	0.03775	
280	8200	29.30	0.03411	
240	7800	32.5	0.03075	
200	7300	36.5	0.02740	
160	6750	42.2	0.02370	
120	6000	50.0	0.02000	
100	5550	55.5	0.01802	
80	4950	61.8	0.01618	
60	4200	70.0	0.01429	
40	3200	80.0	0.01250	
30	2500	83.3	0.01200	
20	1650	82.5	0.01213	
10	600	60.0	0.01666	
1200	12,130	10.1	0.0989	Corrected by reference to the β H curve
700	10,580	15.11	0.0662	

TABLE IX

Nickel—Iron Alloy. Ring No. R-309

Table 9-1: Test for β H curve

H	β	μ	ρ	γ	β/γ
346	12,250	35.4	0.02825		
277	12,250	44.2	0.02260		
208	12,250	58.9	0.01700		
173	12,210	70.6	0.01416	40	305
138.5	12,170	88.0	0.01136	80	152
104.	12,080	116.1	0.00860	170	71
90.	12,060	134.0	0.00746	190	63.4
79.5	11,900	149.8	0.00668	350	34
69.3	11,730	169.5	0.00590	520	22.5
62.3	11,550	185.5	0.00539	700	16.5
55.4	11,390	206.0	0.00485	860	13.2
48.5	11,080	228.5	0.00438	1170	9.46
41.5	10,690	258	0.00388	1560	6.85
34.6	10,250	296	0.00338	2000	5.12
27.7	9600	348	0.00287	2650	3.43
20.8	8830	425	0.00235	3420	2.58
17.3	8370	484	0.00207	3850	2.17
13.85	7820	564	0.001775	4430	1.76
10.4	7210	693	0.001442	5040	1.43
8.65	6780	784	0.001275		
6.93	6380	921	0.001085		
5.54	6020	1085	0.000921		
4.15	5630	1355	0.000738		
2.77	5120	1850	0.000540		
2.08	4780	2300	0.000435		
1.39	4370	3140	0.000318		
0.693	3730	5380	0.000186		
0.415	2950	7100	0.000143		
0.388	2820	7300	0.000137		
0.346	2610	7540	0.000133		
0.319	2330	7300	0.000137		
0.277	1870	6760	0.000148		
0.208	950	4560	0.000219		
0.139	170	1220	0.000820		

TABLE IX—(*Continued*)

Table 9-2: Reconstruction of curve by the law:

$\text{Log}\ \gamma = f - g\ H$

Note: Values of γ, are read from the straight line graph of Fig. 9-2.

H	γ	S	β	μ
10	5040	12,250	7210	721
15	4150		8100	540
20	3450		8800	440
30	2350		9900	330
40	1600		10,650	266
50	1100		11,150	223
60	760		11,490	191.5
70	530		11,720	167.4
80	360		11,890	148.6
90	240		12,010	133.4
100	165		12,085	120.8
110	110		12,140	110.4
120	80		12,170	101.4
130	55		12,195	93.8
140	35		12,215	87.3
150	25		12,225	81.6
160	17		12,233	76.2
170	10		12,240	72.0
180	0		12,250	68.1
190	0		12,250	64.5
200	0		12,250	61.2

TABLE X

Cobalt Iron Alloy: 20 per cent Cobalt

Table 10-1: Test for β H curve

H	β	μ	ρ	γ	D
1500	23,200	15.45	0.0646		
1350	23,200	17.18	0.0582		
1200	23,200	19.33	0.0517		
1050	23,200	22.1	0.0453		
900	23,200	25.8	0.0388		
750	23,170	30.9	0.0324	30	772
660	23,130	35.1	0.0285	70	331
600	23,100	38.5	0.0260	100	231
540	23,050	42.7	0.02342	150	153.5
510	23,000	45.1	0.02217	200	115
480	22,950	47.8	0.02092	250	92
450	22,880	50.8	0.01969	320	71.5
420	22,800	54.3	0.01842	400	55.7
390	22,700	58.2	0.01719	500	45.5
360	22,550	62.6	0.01596	650	34.7
330	22,350	67.7	0.01476	850	26.3
300	22,150	73.8	0.01355	1050	21.1
270	21,900	81.2	0.01233	1300	16.7
240	21,650	90.2	0.01109	1550	13.9
225	21,450	95.3	0.01050	1750	12.25
210	21,300	101.4	0.00986	1900	11.20
195	21,150	108.5	0.00922	2050	10.30
180	20,950	116.4	0.00859	2250	9.3
165	20,730	125.6	0.00796	2470	8.4
150	20,550	137.0	0.00730	2650	7.76
135	20,300	150.3	0.00665	2900	7.00
120	20,050	167.0	0.00598	3150	6.37
105	19,800	187.5	0.00530	3400	5.82
90	19,500	217.0	0.004615	3700	
67.5	19,050	283.0	0.0354	4150	
45.0	18,400	409.0	0.002445	4800	
30	17,750	592	0.00169		
24	17,450	727	0.001375		
18	16,950	942	0.001062		
15	16,550	1103	0.000906		
12	15,900	1325	0.000755		
9	14,850	1650	0.000605		
7.5	14,050	1875	0.000534		
6.75	13,350	1975	0.000505		
6.0	12,800	2130	0.000469		
5.4	12,100	2240	0.000446		
4.8	11,300	2355	0.000425		
4.5	10,850	2410	0.000415		
4.2	10,400	2475	0.000404		
3.9	9750	2500	0.000400		
3.6	9200	2555	0.000391		
3.3	8500	2575	0.000388		
3.0	7750	2580	0.000387		
2.7	6800	2520	0.000397		
2.4	6000	2500	0.000400		
2.1	4950	2360	0.000424		
1.8	3800	2110	0.000473		
1.5	2650	1765	0.000566		
1.2	1600	1330	0.000750		
0.9	800	890	0.001125		
0.6	350	585	0.001710		

TABLE X—(*Continued*)

Table 10-2: Reconstruction of curve by the law $\log \gamma = f - g H$

Values of γ read from straight line graph of Fig. 10-2

H	γ	S 23,200	β	μ
100	5100		18,100	181
150	3450		19,750	131.6
200	2300		20,900	104.6
250	1550		21,650	86.6
300	1050		22,150	73.8
350	700		22,500	64.3
400	470		22,730	56.8
450	320		22,880	50.8
500	210		22,990	45.7
550	140		23,060	41.9
600	95		23,105	38.5
650	65		22,135	35.6
700	45		22,155	33.1
750	30		23,170	30.9
800	20		23,180	28.95
850	13		23,187	27.25
900	10		23,190	25.8
1000	0		23,200	23.2
1100	0		23,200	21.1
1200	0		23,200	19.3

TABLE XI

Cobalt—(Table 8)

Reconstruction by the equation

$\text{Log } \gamma = f - g H$

Table 11-1: Approximate determination of S according to equation $d\beta/dH = a\gamma$

H	β	$\Delta\beta$	ΔH	$\Delta\beta/\Delta H$	B Mean
1600	13,000				
		400	200	2.00	12,800
1400	12,600				
		470	200	2.35	12,365
1200	12,130				
		530	200	2.65	11,865
1000	11,600				
		650	200	3.25	11,275
800	10,950				
		370	100	3.70	10,765
700	10,580				
		380	100	3.80	10,340
600	10,200				

$S = 15{,}350$ by extrapolation; see Fig. 11-1

As the points for the curve β/H as functions of β do not form a very good straight line, the extrapolation is a matter of personal judgment.

TABLE XI—(*Continued*)

Table 11-2: Reconstruction of curve by the law $\text{Log } \gamma = f - g H$, by graphic method

Values of γ read from graph of Fig. 11-2

H	γ	S	β
100	7600	15,300	7700
200	7000		8300
300	6500		8800
400	6000		9300
500	5500		9800
2000	1700		13,600
2500	1150		14,150
3000	770		14,530
4000	350		14,950
5000	160		15,140
6000	70		15,230
7000	30		15,270
8000	15		15,285
9000	5		15,295
10,000	0		15,300

TABLE XI—(*Continued*)

Table 11_3: Reconstruction of curve by the law $\log \gamma = f - g H$, by the analytical method

Determination of f and g

H	β	S	γ	$\text{Log } \gamma$	Δ Log γ	g	$g H$	f
600	10,200	15,300	5100	3.7075	0.346	.000346	0.2076	3.9155
1600	13,000		2300	3.3615			0.5536	3.9155

Table 11-4: Reconstruction and extrapolation of the βH curve

H	g	$g H$	f	$\log \gamma$	γ	S	β	μ
100	.000346	0.0346	3.9155	3.8805	7600	15,300	7700	77
200		0.0692		3.8459	7010		8290	41.5
300		0.1038		3.8113	6480		8820	29.4
400		0.1384		3.7767	5980		9320	23.3
500		0.1730		3.7421	5522		9780	19.6
600		0.2076		3.7075	5100		10,200	17.0
700		0.2422		3.6729	4710		10,590	15.1
800		0.2768		3.6383	4350		10,950	13.7
1000		0.3460		3.5691	3708		11,592	11.6
1200		0.4152		3.4999	3160		12,140	10.1
1400		0.4844		3.4307	2695		12,605	9.0
1600		0.5538		3.3615	2300		13,000	8.13
2000		0.692		3.2231	1670		13,630	6.82
2500		0.865		3.0501	1125		14,175	5.67
3000		0.6038		2.8771	755		14,545	4.85
4000		1.384		2.5311	340		14,980	3.74
5000		1.73		2.1851	160		15,140	3.03
6000		2.075		1.8401	70		15,230	2.54
7000		2.422		1.4903	30		15,270	2.18
8000		2.768		1.1461	15		15,285	1.91
9000		3.115		1.8001	5		15,300	1.70
10,000		3.460			0		15,300	1.53
12,000		4.152			0		15,300	1.28

TABLE XI—(*Continued*)

Cobalt Pure (Table 8)

Table 11-4: Reconstruction of curve by Frolich's Law on the basis of two points at $H = 1200$ and 1600

(1) Determination of constant h and S.

H	β	μ	$\Delta\mu$	β	h	γ μh	S $(\beta+\gamma)$	γ	$S.h$
1600	13,000	8.125	1.985	870	438.3	3560	16,580	3560	7,260,000
1200	12,130	10.11				4430	16,560	4430	

(2) Reconstruction of βH curve.

H	$H+h$	$S.h$	γ	S	β
		7,260,000		16,560	
100	538		13,500		3060
200	638		11,380		5180
300	738		9840		6720
400	838		8670		7890
500	938		7740		8820
600	1038		7000		9560
700	1138		6380		10,180
800	1238		5860		10,700
1000	1438		5050		11,510
1200	1638		4430		12,130
1400	1838		3950		12,610
1600	2040		3560		13,000
2000	2440		2980		13,580
2500	2940		2470		14,090
3000	3440		2110		14,450
4000	4440		1635		14,925
5000	5440		1335		15,225
7000	7440		975		15,585
10,000	10,440		695		15,865
20,000	20,440		355		16,205
30,000	30,440		240		16,320
40,000	40,440		180		16,380

TABLE XII

Electrolytic Iron

Sample: Yensen-rod 1413-*A*

Test made at the Bureau of Standards

Table 12-1: (Test No. Tem. 41893)

Original data for *H* and *B* received through courtesy of Dr. T. D. Yensen, and computation of β, μ and γ made by S. L. Gokhale

H	*B*	β	μ	ρ	γ	*D*
0.2	460		2300.	0.000435		
0.4	4600		11500.	0.000087		
0.5	7300		14600.	0.0000685		
1.0	11,150		11150.	0.0000985		
2.0	14,230		7115.	0.000141		
4.0	15,770		3940.	0.000254		
20.0	17,020	17,000	850.	0.00118	4500	3.78
100.	18,700	18,600	186.	0.00537	2900	6.40
200.	19,960	19,760	99.	0.0101	1740	11.34
400.	21,320	20,920	52.3	0.0191	580	36.1
600.	21,900	21,300	35.5	0.0282	200	105.5
1000.	22,500	21,500	21.5	0.0465	0	
1500.	23,000	21,500	14.3	0.0700	0	
2000.	23,500	21,500	10.7	0.0935	0	
2500.	24,000	21,500	8.6	0.116	0	

TABLE XII—(*Continued*)

Table 12-2: Reconstruction of the curve by the Logarithmic law

Note: Values of γ read from the straight line graph of Fig. 12-3.

H	γ	*S*	β	μ
20	4500	21,500	17,000	850.
50	3850		17,650	353.
100	2930		18,580	185.8
150	2240		19,260	128.4
200	1710		19,790	98.95
250	1310		20,190	80.4
300	1000		20,500	68.3
350	760		20,740	59.3
400	585		20,915	52.3
450	450		21,050	46.8
500	340		21,160	42.3
600	200		21,300	35.5
700	115		21,385	30.5
800	70		21,430	26.8
900	40		21,460	23.85
1000	20		21,480	21.5
1100	10		21,490	19.5
1200	0		21,500	17.9
1500	0		21,500	14.3
2000	0		21,500	10.7
2500	0		21,500	8.6

TABLE XII—(*Continued*)

Electrolytic Iron (Yensen)

Table 12-3: Comparison of two samples of nearly identical magnetic character

Tests at Bureau of Standards

Test No. Tem. 41893

	Rod No. 1413-*A* (Annealed)				Rod No. 1413-*B* (Unannealed)			
H	*B*	β	μ	ρ	*B*	β	μ	ρ
2500	24,000	21,500	8.6	0.1162	24,100	21,600	8.64	0.1157
2000	23,500	21,500	10.7	0.0935	23,600	21,600	10.8	0.0926
1500	23,000	21,500	14.3	0.0700	23,100	21,600	14.4	0.0694
1000	22,500	21,500	21.5	0.0465	22,600	21,600	21.6	0.0463
600	21,900	21,300	35.5	0.02815	22,000	21,400	35.7	0.02800
400	21,320	20,920	52.3	0.01913	21,370	20,970	52.4	0.01910
200	19,960	19,760	99.0	0.01010	19,950	19,750	98.7	0.01013
100	18,700	18,600	186.0	0.00538	18,600	18,500	185.0	0.00541

TEMPERATURE AFFECTS RADIO SIGNAL STRENGTH

That temperature influences the strength of radio signals is the conclusion reached by L. W. Austin and Miss Wymore of the Bureau of Standards, Department of Commerce. This work is a part of the program of the International Union of Scientific Radio Telegraphy, which was adopted at Brussels in 1922 and is now being carried on in the various countries belonging to the Union.

Two years ago, Dr. Austin described a decided increase in the signals received at Washington from the Radio Corporation transatlantic stations at Tuckerton and New Brunswick, N. J., during the passage of severe cold waves over the eastern states. Further study now indicates that whenever the temperature rises along the signal path there is a tendency for the signal to drop; and conversely, a falling temperature tends to produce a stronger signal, though these temperature effects are often masked by other unknown influences.

Experiments on the relations existing between meteorological phenomena and radio transmission require preferably at least fairly uniform meteorological conditions between the sending and receiving stations. For this reason, stations between 125 and 190 mi. distant were chosen for the experiments, rather than stations at great distances. On the other hand, stations much less than 125 mi. distant would probably not have shown the influence of weather changes to so marked an extent.

There seems to be no doubt that the temperature changes influence the waves which are reflected or refracted from the Kennelly-Heaviside layer, 60 mi. or more above the earth's surface rather than the waves which glide along the ground, since no marked change is observed in signal intensity due to long continued rain or drought, the presence of snow, or the presence or absence of frost in the ground.

ELECTRICITY USED TO RUSH FLOWERS

Turning a dark cellar into a bright solarium and growing tropical plants in greenhouses 5000 mi. north of their native habitat are realizations. These things have been done with the aid of electric light. In an experimental greenhouse in Yonkers, N. Y., all sorts of weird results have been obtained by running a traveling crane up and down all night over the glass roof, flooding electric light in varying intensities over beds of plants and flowers from the four corners of the earth. About 100,000 candle power made sweet peas bloom five weeks ahead of their daytime schedule. Oriental clover that requires two years to bloom under natural conditions blossomed in two months under 24 hours of daily light. Orchids were produced at will and brought to fullest flower on certain fixed schedules, thus presaging strange doings in the horticulture of the future by electric agents.

Abridgment of

An Investigation of Transmission-System Power Limits

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***Synopsis.**—Results of theoretical analysis, verified by miniature-system tests of the power limits of transmission systems, are discussed, among the major conclusions being the following:*

The criterion for stability under all conditions is the steady-state power limit.

The charging kv-a. exercises marked detrimental effects on stability.

The characteristics of synchronous terminal apparatus are of great importance.

Improvements can be made by modifying present apparatus design.

Automatic voltage regulators, suitable exciters, and fast relays are essential.

The mercury-arc rectifier, as an adjunct in excitation circuits, shows real advantages.

Introduction

The subject of transmission-system power limits and related problems is one of utmost importance in present and future projects, as emphasized by recent papers.[2]

The present paper deals with the results of careful theoretical analysis and calculations, verified by extensive miniature-system tests, of the power limits of transmission systems. Theoretical studies have been checked by tests on a miniature system equipped with synchronous apparatus, lines of variable constants, exciters, regulators, etc., and so chosen that 2300 volts and 180 kilowatts corresponded to 220,000 volts and 15,000 kw. on the actual system. The work covered was planned and directed by Messrs. R. E. Doherty and H. H. Dewey, and to a large extent outlined by them in a recent paper before the Institute.[3]

In addition to investigations relating to a basic knowledge of power limits of systems, attention has been focused on methods of improving their stability—in other words, increasing the power limits. In this connection, careful analysis has been made of special types of synchronous equipment, voltage-regulation schemes, induction generators, use of static condensers for the compensation of line inductive reactance, and many other devices. The work has been paralleled throughout by studies of actual projects.

In the computation of power limits, a thorough knowledge of the theory of synchronous machines is essential. It can be shown that, for all practical purposes, it is unimportant whether salient-pole or cylindrical-rotor theory be used in the calculation of all quantities but angular relationships. As steady-state power-limit studies made by the authors have not involved angular relationships, the use of either theory is justified. In transient problems, however, angular relationships are of fundamental importance and, hence, the appropriate theory must be used.

A large amount of work has also been done on the power-angle characteristics of synchronous machines. Papers dealing with these studies, and synchronous-machine theory, will, it is hoped, be presented before the Institute in the near future.

Among the important conclusions reached as a result of the investigations made by the authors, and other interested engineers of the General Electric Company, may be mentioned:

1. Too great importance must not be attached to the transmission line as it is but one link in the circuit; the characteristics of terminal apparatus, such as synchronous machines, and methods of voltage regulation are of equal, if not greater, importance.

2. The only feature in which the stability of high-tension long-distance transmission and high-tension cable systems differs from that of any other type is in the limitation of the excitation of synchronous apparatus due to the charging kv-a. of the lines.

3. For slowly-applied loads, automatic voltage regulators and suitable exciters permit stable operation up to the same limit which can be obtained with manual control.

4. The problem of obtaining greater power limits offers two avenues of approach:

(*a*) Modification of the characteristics of existing synchronous apparatus and transmission lines.

(*b*) The development of new methods of voltage regulation.

5. Extensive miniature-system tests indicate that, no matter how fast load is applied, under similar conditions of excitation or voltage the power limit is always the same as the steady-state limit. In view of these results and experience, it appears that the

1. Both of General Electric Company, Schenectady, N. Y.

2. Groups of Papers presented at A. I. E. E. Conventions at Philadelphia, February, 1924, New York, February, 1925, and Seattle, Sept., 1925.

3. *Fundamental Considerations of Power Limits of Transmission Systems*, R. E. Doherty and H. H. Dewey, Jour. A. I. E. E., Vol. XLIV, October, 1925, p. 1045.

Presented at the Midwinter Convention of the A. I. E. E., New York, N. Y., February 8-11, 1926. Complete copies available upon request.

fundamental criterion of power-system stability is the final steady-state power limit.

6. Adequate speed of relaying is the vital factor in the maintenance of stability during system short circuits.

7. Reliable methods of calculation of system power limits, for steady-state conditions, are available. For the more complicated networks, a-c. miniature systems give excellent results.

8. At present there are no satisfactory methods of computing system power limits, under transient conditions, for any but the simplest cases. However, it is possible to study completely all transients ensuing from disturbances which do not result in instability, by means of the electromechanical analyzer.

Methods of Calculation

It has been indicated that reliable methods of determining system steady-state power limits are now available. In general, it has been found that the method of calculation adopted by the authors gives results of good engineering accuracy, as shown by the computed and test values given in this paper. Furthermore, these results agree very well with those secured by independent investigators using other schemes of analysis.

Calculations of system steady-state power limits are comparatively easy for simple systems comprising, say, one generating station, a line or two, and one receiving station. Where several branches are involved, analysis becomes more difficult; partial solutions by graphical methods are combined to give a complete solution. When the system under consideration comprises many branches, computation by these graphical methods becomes practically impossible and resort must be had to analysis by miniature a-c. systems.[4] Steady-state stability problems can be solved with the aid of miniature a-c. systems of the same order of size as the d-c. short-circuit calculating table, which has been of such invaluable aid.

For the study of system transients arising from dropping a line, suddenly adding a load, etc., there is no practical scheme of analysis available for any but the simplest cases. The unwieldiness of the step-by-step method[5] increases very rapidly with the number of elements in the system, and it soon becomes impossible of application. However, by using the equivalent-circuit idea,[6] it is possible to study the electromechanical transients in any system, no matter how complicated, for loads below the power limit; that is, where the differential equations for the system are linear.

4. *Artificial Representation of Power Systems,* H. H. Spencer and H. L. Hazen, Jour. A. I. E. E., Vol. XLIV, January 1925, p. 24.

5. *Power System Transients,* V. Bush and R. D. Booth, Jour. A. I. E. E., Vol. XLIV, March 1925, p. 229.

6. *Oscillographic Solution of Electromechanical Systems,* by C. A. Nickle, Jour. A. I. E. E., Vol. XLIV, December, 1925, p. 1277.

Description of Miniature System And Methods of Testing

When the investigation was commenced, it was realized that means should be available for verifying promising leads developed in analytical studies, and establishing the reliability of methods of calculation. Inasmuch as it was not feasible to use an actual system for this work, a miniature system of sufficient capacity to give reliable test information was set up in the factory. The equipment included several 225-kv-a. synchronous motors with direct-connected d-c. generators, units for setting up any type of line, exciters, standard vibrating-contact regulators, etc. By using the d-c. generator of a set as a motor supplied from the shop bus, and the corresponding unit of another set as a separately-excited generator supplying a water-rheostat load, it was possible to study systems comprising four synchronous units. The use of resistance loads prevented any possibility of hunting due to a feed back on the shop bus. For simulating an infinite generator, a 10,000-kv-a. alternator was available.

To correlate results obtained by miniature test with corresponding values for the actual system, it should be borne in mind that the miniature system was designed so that a voltage of 2300 corresponded to 220 kv. on an actual system; similarly, 180 kw. was equivalent to 150,000 kw.

Steady-State Studies

It is evident that any analysis of transmission-system power limits falls into two major divisions—one dealing with the limits obtaining for slowly-applied loads, as in steady-state operation, and the other with the limits for transient-state, suddenly-applied loads. Accordingly, the treatment of the subject in this paper follows more or less the above division.

Influence of Circuit Elements on Power Limits. The first system studied was a simple, two-machine system consisting of two 225-kv-a. units connected directly together, electrically. The machines were synchronized, the excitations adjusted to the desired values and maintained constant at those values, together with system frequency, as the load was slowly increased by increasing the d-c. generator excitation.

The next step consisted of the introduction of lines of various constants, proportional to different lengths of the actual 220-kv. transmission line. By computing the power-voltage curves for a system comprising an alternator, a line, and a synchronous motor, it was possible to determine the effect of the added impedance on the power limit. No effort was made to include the capacity susceptance of the actual line in the first analysis; this was done later. The constants of these lines, designated *L-R* lines, were as follows:

125-mi. *L-R* line $z_L = 1.27 + j\ 9.25$ ohms
250-mi. *L-R* line $z_L = 2.54 + j\ 18.5$ ohms
500-mi. *L-R* line $z_L = 5.09 + j\ 37.0$ ohms

A comprehensive idea of the relative effect of the various circuit elements on power limits can be gained by a study of Table I, which summarizes representative results for the different systems discussed.

The values given in Table I are self-explanatory. They indicate, among other things:

1. The importance of voltage regulators if the maximum possible operating capacity is desired.
2. That transmission-line impedance plays a large part in reducing the maximum power limit but that the synchronous-apparatus characteristics are equally important.
3. That transmission-line capacity susceptance reduces the power limit considerably.

TABLE I
COMPARATIVE POWER LIMITS

System	Excitation	Pull-out Power-Kw. Calculated	Pull-out Power-Kw. Test
1. Alternator and motor on same bus	Normal excitations	115	129
2. Alternator and motor on same bus	Normal regulators	280	—
3. Alternator, 125-mi. L-R line, motor	Normal excitations	99	107
4. Alternator, 125-mi. L-R line, motor	Normal regulators	—	260
5. Alternator, 250-mi. L-R line, motor	Normal excitations	85	89
6. Alternator, 250-mi. L-R line, motor	Normal regulators	168	155
7. Alternator, 500-mi. L-R line, motor	Normal excitations	65	68
8. Alternator, 500-mi. L-R line, motor	Normal regulators	110	104
9. Alternator, 250-mi. "nominal π" line, motor	Normal excitations	76	75
10. Alternator, 250-mi. "nominal π" line, motor	Normal regulators	144	134
11. Infinite generator, 250-mi. L-R line, infinite receiver	Normal regulators	283	—
12. Infinite generator, 250-mi. L-R line, normal motor	Normal excitations	—	125
13. Normal generator, 250-mi. L-R line, infinite receiver	Normal regulators	213	—

Sufficient has been said in the preceding discussion to indicate that a system with a number of machines operating in multiple should have a higher power limit than the simple straightaway transmission by virtue of the fact that the generating bus, or receiver bus, tends to become an infinite bus, a fact verified by investigation. Table II illustrates the effect of adding multiple generators and summarizes the power limits for a number of systems.

Use of Voltage Regulators. A brief survey of the comparative power limits given in Table I will indicate the advantage of operating a system at normal terminal voltage rather than normal excitations. It is not, of course, intended to infer that systems are so operated but merely to establish bench-marks to indicate the advantage, with respect to power limit or stability, of constant-voltage operation. As noted, the ratio of the normal-regulator power limit to the normal-excitation power limit varies from 2.5 to about 1.6, depending on the relative impedance of the circuits.

In view of the importance of maintaining those excitations which correspond to normal terminal voltage at the load being carried, it seems well to discuss at this point the mechanism of the operation by which the regulator maintains constant terminal voltage. Referring to Fig. 1, a number of power-voltage curves, with excitation as parameters, are shown. Suppose the system to be operating with excitation (i_4) and load (P_2). An increase in load of about 20 per cent will cause pull-out at that power at which $\dfrac{dP}{dE} = 0$. To carry a load greater than that causing pull-out at excitation (i_4), it is necessary to increase the excitation to, say, (i_6). In this case pull-out will occur at a load (P_3).

TABLE II
EFFECT OF MULTIPLE UNITS

System	Excitation	Pull-out Power in Kw. Calculated	Pull-out Power in Kw. Test
1. Alternator on same bus as motor	Normal excitations	115	129
2. Alternator and motor on same bus with addition of shunt synchronous condenser	" "	140	145
3. Alternator supplying two motors on same bus*	" "	157†	145†
4. Two alternators‡ supplying one motor on same bus	" "	155†	145†
5. Alternator, 250-mi. L-R line, and motor	Normal regulators	168	155
6. Two alternators‡ in multiple, 250-mi. L-R line, and motor	" "	—	192

*Approximately equal division of load.
†Total load.
‡Equal division of load.

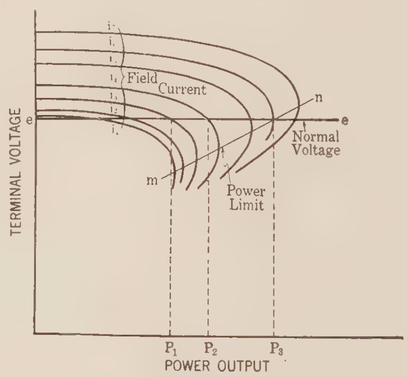

FIG. 1—TYPICAL CONSTANT-EXCITATION POWER-VOLTAGE CURVES

While it is possible to manually adjust the excitations for slowly-increasing loads, this is not feasible where rapid load additions may occur. Resort must accordingly be made to some automatic device which will rapidly adjust the excitation to the value corresponding to the actual load and the desired operating voltage. Such a device is the vibrating-contact type voltage regulator. It will be interesting to examine its operation.

As is well known, the voltage regulator is designed to maintain constant voltage at some point on a system—in this case, the supply and receiver busses. This is accomplished by increasing the excitation of the proper machine when the voltage at the regulated bus drops or vice versa. However, at any constant load, power factor and voltage, there is a definite excitation required, namely, that given by the intersection of the co-

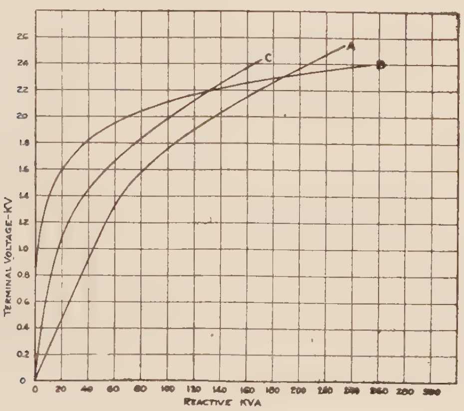

Fig. 2—Voltage-Reactive Kv-a. Characteristic Curves for Various Reactors

Curve *A*—184 kv-a. unsaturated reactor
" *B*—184 " saturated reactor
" *C*—225 " synchronous condenser with 1.0 ampere field current

ordinates corresponding to power and voltage. In other words, the voltage regulator adjusts conditions by causing a transfer of operation from one constant-excitation (power-voltage) curve to another. It follows, then, that pull-out will take place at the intersection of the straight line representing the constant operating voltage with the locus of pull-out points, *i. e.*, power (P_3) and voltage (e), corresponding to excitation (i_6). This is the maximum power which can be delivered by the system at voltage (e). With imperfectly adjusted regulators, however, pull-out will take place at some power less than (P_3).

It must be borne in mind that system operation with voltage regulators consists of nothing more than a succession of steady-states, each with some particular constant value of excitation. If, for any reason, the regulators are unable to adjust conditions to those corresponding to stable operation, at any load, pull-out will take place along the power-voltage curve corresponding to the particular excitations then obtaining.

The preceding discussion will emphasize the vital necessity for voltage regulators on systems which it is desired to operate at loads close to the maximum power at the system voltage. This point has been demonstrated by actual experience on systems.

Influence of Machine Nominal Voltages on System Stability. Analysis of the preceding investigations led to the conclusion that system stability could be improved by increasing the machine nominal voltages for any particular terminal voltage. Two simple methods of accomplishing this were available, namely, the use of static shunt reactors and synchronous reactors (condensers). Accordingly, the use of such devices was investigated and a number of tests made.

The increase in power obtained by means of a shunt reactor is due to the greater excitation required to maintain a given terminal voltage for given power conditions. This increased excitation could be obtained more economically by lengthening the air-gap of the machine.

Similar results were obtained using an under-excited synchronous condenser in place of the shunt reactor. The current taken by a synchronous condenser is the difference between the terminal voltage and the nominal voltage divided by the synchronous reactance. When the nominal voltage is zero, the current is just the terminal voltage divided by the synchronous reactance, and the current-voltage curve is identical with that of a static reactor.

Having shown the effect of reactors, either static or synchronous, in increasing machine nominal voltage, studies of systems with lines were undertaken. The static reactors considered were of two types:

a. Unsaturated iron-core reactor
b. Saturated iron-core reactor

In Fig. 2, characteristic curves for the actual reactors used are compared with a corresponding curve for the synchronous condenser.

The advantage of using a saturated iron-core reactor[7] lies in the fact that the rate of change of reactive kv-a. consumed with respect to terminal voltage is much greater than for the ordinary non-saturated reactor. In other words, at normal voltage, the kv-a. consumed by the two types of reactor is the same, but at a lower terminal voltage, the kv-a. taken by the saturated reactor is much less. Therefore, any disturbance in the system producing a voltage decrease will cause a reduction in the armature reaction of the synchronous equipment, due to the reactive kv-a. taken by the reactor, thus making an increase in machine excitation available for maintaining stability.

With an appreciation of the effect of shunt reactors on system power limits, it is quite easy to see why the line capacity susceptance should reduce the power limit.

7. *Theory of D-C. Exciter Iron-Core Reacters and Regulators*, by A. Boyajian, Trans. A. I. E. E., Vol. 43, 1924, p. 919.

The Application of the Saturated-Core Reactor Regulator, by D. K. Blake, A. I. E. E., Vol. 43, 1924, p. 937.

Losses in Iron Under the Action of Superposed A-C. and D-C. Excitations, by O. C. Charlton and J. E. Jackson, Jour. A. I. E. E., Vol. 44, Nov. 1925, p. 1220.

Consider a system which simulates an actual 250-mi. straightaway system in which the actual line is replaced by the "nominal π" line. The capacity susceptance is, so far as its effect on the machine nominal voltages is concerned, simply a *negative* shunt reactance of about 70 ohms, reducing the required excitation for a given terminal voltage.

In this connection, it is interesting to consider the effect of adding multiple lines between generating and receiving equipment of a given kv-a. rating. Due to the increase of charging kv-a. with numbers of lines, a point is soon reached where the decrease of machine excitations more than counterbalances the effective decrease in line reactance. When the number of parallel lines is increased beyond this point, a reduction in the power limit occurs. Fig. 3 illustrates this condition.

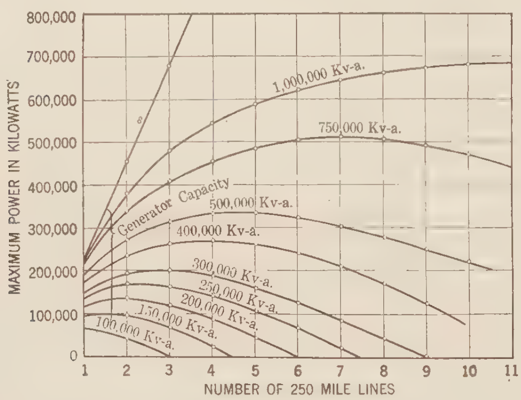

Fig. 3—Maximum Power Which can be Transmitted 250 Miles at 220,000 Volts, Shown as a Function of the Capacity of Synchronous Apparatus, and the Number of Transmission Circuits

It is evident that shunt reactors may be used to compensate for the effect of the leading kv-a. taken by the line capacity susceptance, and thus improve the power limit. Actual studies of reactors and synchronous condensers on large projects indicate that the reactors may be the more advantageous, on the score of economy. As previously pointed out, the same result can be gained by lengthening the air-gap of the synchronous apparatus.

"Saturated" Machines. It should be evident from the preceding discussion that *any measure by which the field current can be increased with the same terminal voltage will improve the stability.* Several methods of accomplishing this have been mentioned under the head of "Influence of Machine Nominal Voltages on System Stability." In addition to methods previously discussed, there is another—that is, increasing the degree of saturation of the poles.

Consider the saturation curves of two synchronous machines as shown in Fig. 4, one for a "normal" machine with operatng range on the saturation curve somewhat below the knee, the other with normal voltage well above the knee. Furthermore, the machines will be of identical design except in so far as the cross-sectional area of the poles is concerned.

If the two machines be operated separately as generators with such field currents that normal terminal voltage occurs at no load, identical power increments on each will not cause the same lowering of the terminal voltage. In other words, *the saturated machine is stiffer.*

Such tests as were made indicate that the benefits obtained by the use of synchronous generators and motors with saturated poles are of the same order as could be obtained by lengthening the air-gap.

Use of Induction Generators on Transmission Systems. Induction generators have been suggested from time to time for use in connection with long transmission lines, but they have never come into practical use. During the course of the present investigation it was felt that there were certain merits in such use which should be carefully investigated. As known now, the power which can be transmitted over a line between two synchronous machines is limited by the phase relationships of the system. With the induction generator, however, the power delivered from the prime-mover shaft to the generator terminals depends upon the difference in speed of the prime mover and the terminal-voltage vector. With a prime mover and a rotor capable of transmitting any desired power from the prime-mover shaft to the stator circuit, the power limit will be dependent upon the angle between the rotor of the receiver-end motor and the air-gap flux of the generator. That is, the power limit of synchronous-to-synchronous transmission is a function of the angle between the machine rotors but with induction-synchronous transmission is dependent upon the angle between induction generator air-gap flux and synchronous motor rotor.

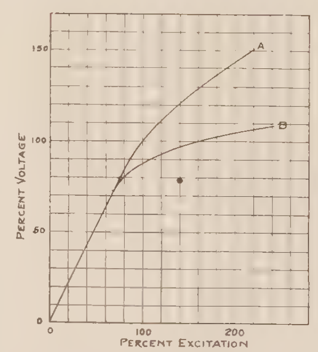

Fig. 4—Open-Circuit Characteristic Curves
Curve *A*—Normal generator
Curve *B*—Saturated generator

Although economic studies may indicate a possible margin in favor of the induction generators, there is practically no advantage to be gained by their use, so far as stability is concerned.

"Loaded" Transmission Systems. In recent years much attention has been given to the possibility of increasing the stability of power systems by the use of synchronous condensers at intermediate points.[8] Investigations made by the authors indicate that greater gains have been ascribed to such use of synchronous condensers[9] than is actually the case.

The addition of a synchronous condenser of the same rating as the terminal apparatus to the simple 500-mile *L-R* straightaway system increases the power limit at normal voltage from 110 kw. to 150 kw. or about 36 per cent. It must be remembered, however, that on actual systems, the synchronous condensers at loading points would ordinarily have a much smaller capacity than the terminal apparatus. Consequently, the percentage increase in power limit will be much less. Moreover, actual systems have lines with distributed capacitance which tends to accomplish the same object as the loading condenser. In other words, to secure any appreciable increase in maximum power of actual systems, the condenser used for loading must have a kv-a. capacity much higher than indicated by early investigations[10].

Like most problems of this type, the advantages of loading condensers, for any particular project, cannot be definitely stated without a careful economic study.

"Resistance" Loading of Transmission Systems. All the systems discussed so far have had synchronous motor loads—in other words, typical shaft loads, which have constant kilowatt and variable reactive kilovolt-ampere consumption; that is, the power is independent of the voltage. No reference has been made to high power-factor admittance loads, such as lighting, industrial heating, etc. It will, therefore, be interesting to turn attention for a few moments to the question of such loads—"resistance" loads—for long transmission systems.

Consider two synchronous machines tied together through an impedance. It is well known that the limit of stability occurs at the point at which $\frac{dP}{dE} = 0$, a fact verified many times by test. The criterion for maximum power, $\frac{dP}{dE} = 0$, holds only where power is the independent variable, as in shaft loads. Suppose, however, that one of the synchronous machines in this combination is replaced by a dead impedance load. Then, instability will *not* occur at the point where $\frac{dP}{dE} = 0$, nor at any other point, since for a dead load there is nothing with which the generator can fall out of step. There will, however, be a *maximum power* point for constant excitation on the generator. If voltage is maintained at the load by a synchronous condenser, it can be shown that instability will occur where $\frac{dR}{dE} = 0$, instead of $\frac{dP}{dE} = 0$, where the resistance (R) of the dead load is the independent variable.

The importance of choosing the proper criterion can be better appreciated if it is understood that a pure resistance load with a synchronous condenser for voltage regulation is equivalent to an infinite bus, as far as maximum power under steady-state conditions is concerned. This statement is true only when there is no other load on the system. To emphasize the importance of choosing the proper criterion, a system comprising both resistance and shaft loads may be cited.

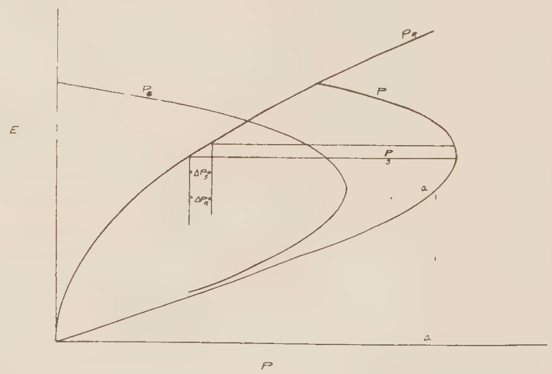

FIG. 5—TYPICAL POWER-VOLTAGE CHARACTERISTICS FOR SYSTEM WITH COMPOSITE SHAFT AND RESISTANCE LOAD

In such a case, consider what happens when the shaft load is increased. Any increment of shaft load results in a decrease of terminal voltage and, hence, a decrease in power consumed by the resistance load. A set of typical power-voltage characteristics of a system with both shaft and resistance load is shown in Fig. 5. Curve (P) represents the variation of total power with voltage, (P_R) the variation of resistance power with voltage, and (P_S) the variation of shaft power with voltage. It is evident from the figure that the slope of the curve of total power becomes infinite—that is, $\frac{dP}{dE} = 0$—at that point where an increase of shaft power is exactly equal to the resultant decrease in resistance power. However, *the system is still stable,* inasmuch as the slope of the curve of shaft power has not yet become infinite, and (P_S) *is*

8. *Voltage Regulation and Insulation for Large Power Long Distance Transmission Systems,* by F. G. Baum, TRANS. A. I. E. E., Vol. 40, 1921, p. 1017.

9. *Some Theoretical Considerations of Power Transmission Systems,* by C. L. Fortescue and C. F. Wagner, TRANS. A. I. E. E., Vol. 43, 1924, p. 16.

"*Power Limitations of Transmission Systems.*" by R. D. Evans and H. K. Sels, TRANS, A. I. E. E., Vol. 43, 1924, p. 26.

the independent variable. Breakdown occurs where

$$\frac{d\,P}{d\,E} = 0,$$

and the total power is as shown by the ordinate $(a\,a')$. In other words, a system with such a composite load may be stable even though operation is on the under side of the total power-voltage curve.

Compensation of Transmission-Line Inductive Reactance. Preceding discussion has shown the effect of the reactance of long transmission lines in limiting the amount of power which can be transmitted with stable operation. It is, then, apparent that any means by which this effect could be economically reduced would be advantageous. It is possible to reduce the line reactance by use of special line construction[10]. However, the decreased line reactance is gained at the expense of an increase in charging kv-a., which may partially offset or even more than offset the advantage gained.

However, by introducing series static condensers into the line[11], it is possible to effectively neutralize or compensate for the effect of line inductive reactance without any increase in charging kv-a. There are certain difficulties attendent upon such use of static condensers, as protection from excess voltages during short circuit. Careful investigations show the feasibility of series static condensers for this service hinges almost entirely on over-all economy.

Influence of Methods of Voltage Regulations on Stability. Careful analysis of the effect of various circuit elements, and special types of apparatus, on transmission-system stability, as discussed elsewhere in this paper, will indicate that the real criterion of stability is the inherent slope of the power-voltage characteristic. In other words, instability occurs when the slope of the power-voltage curve is such that

$\frac{d\,P}{d\,E} = 0$, for shaft loads. How can this occur in a power system, the synchronous machines of which are provided with automatic voltage regulators?

As pointed out under "Use of Voltage Regulators," the regulator is merely a device for shifting the system from one constant-excitation condition to another, as dictated by the terminal voltage. Referring to Fig. 1, voltage is maintained by the regulator functioning in such a way that the system operates along the line (ee) by passing from one constant-excitation state to another. However, and this is the important point, the inherent stability of the system is not that indicated by the slope of the line (ee)—*i. e.*, $\frac{d\,E}{d\,P} = 0$— but by the slope of some constant-excitation curve. It may be anyone of a number as shown, but it is always some one of the family of curves. It is in just this respect that regulated machines do not have the characteristic of an infinite bus with $\frac{d\,E}{d\,P} = 0$, the ideal type of voltage regulation.

In this connection, it will be of interest to examine the phenomena accompanying an increase of load on a piece of synchronous apparatus in a transmission system. Such an increase in load will result in a decrease in terminal voltage with a given excitation.

Now the voltage regulator is not responsive to the rate of change of voltage, but only to a value of voltage —the function itself; hence, it increases the excitation in the degree necessary to compensate for the increased armature reaction due to load only after the lapse of an appreciable time. That is, the field excitation is increased only after the voltage has dropped. Such investigations as made by the authors do no indicate that any appreciable gain in power limit can be secured by reducing the time constant of the excitation system below that of normal equipment. Compensation for increased load, and, hence, armature reaction, always lags behind the cause. This is important during transients and especially near the point of intersection of (ee) and (mn)—the point of pull-out. It is the reason why a system with regulated generating stations cannot be considered as having infinite supply busses and hence a power limit equal to that of the line itself.

Consider what happens when load is added to a d-c. generator provided with a compensating field winding. Simultaneously with the increase in armature reaction, a magnetomotive force is set up in opposition to it. Depending on the size of the compensating field, the effect of increased load may be entirely counterbalanced or compensated for—even over-compensated. A similar case is that of a circuit in which the inductive reactance is exactly balanced by an equal series capacitive reactance. What happens when the circuit load is increased? The voltage drops across both inductive and capacitive reactances increase simultaneously, but being of opposite phase, effectively neutralize each other. With respect to the terminals, there is no reactance drop.

Applying the principle enunciated above—*i. e.*, the effective neutralization of the cause by making the effect take place simultaneously—to synchronous equipment, the great importance of it can be seen. The machines in effect would have infinite capacity, limited only by heating and mechanical considerations. To realize the significance of this, refer to Table I and related discussion, where it is pointed out that the power limit of a 250-mi. miniature *L-R* line by itself is

10. *Output and Regulation of Long-Distance Lines*, Percy Thomas, TRANS. A. I. E. E., Vol. 28, 1909, p. 615.

11. Discussion by T. A. E. Belt on "*Present State of Transmission and Distribution Developments*," JOUR. A. I. E. E., Vol. 44, October, 1925, p. 1153.

283 kw., but with normal machines, only 168 kw. That is, the synchronous reactance of the machines reduces the power limit about 41 per cent. In actual systems, the effect of the generating and receiving equipment might even increase this value to 50 per cent.

It is evident that if some device can be applied to synchronous apparatus which will prevent a reduction of the net ampere turns tending to force flux through the magnetic circuit, such a device will effectively decrease the effect of armature reaction which is so detrimental to the stability and power limits of long transmission systems. That is, as load builds up, the armature reaction builds up, but simultaneously and due to exactly the same causes, the field ampere-turns must build up with the right magnitude and space phase to compensate for the armature reaction. *The perfect simultaneity of cause and effect effectively neutralizes armature reaction.*

Of course, to obtain the ideal in voltage regulation, the inherent reactance of synchronous machines must also be neutralized—as by the use of series static condensers of suitable capacity—in the same way that the effect of line reactance may be overcome.

It is apparent that it is somewhat difficult to completely accomplish what has been outlined above—for the effective compensation of armature reaction necessitates the application of field ampere-turns in the proper space phase and varying in magnitude and time with the armature reaction. It was realized, however, that any device which would increase the excitation in exact proportion to the armature reaction—or line current—and in perfect simultaneity with it, should be of considerable advantage.

Accordingly, a number of devices and methods for accomplishing this object were carefully investigated. Finally, it was decided that ordinary mercury-arc rectifiers used as adjuncts in the otherwise normal excitation circuits of synchronous apparatus appeared to offer the greatest promise.

The use of mercury-arc rectifiers has shown, in factory tests, that a very appreciable gain in stability and power limits can be secured. While practical application on power systems has not yet been made, it is confidently believed that at least a 50 per cent reduction in effective armature reaction can be secured. Moreover, a real scheme of voltage regulation, effective under steady and transient conditions, is for the first time made available.

Transient Studies

When the question of the stability of power-transmission systems recently came to the fore, it was thought that the worst condition of operation likely to be faced would be that obtaining during transient conditions. Such a transient state might arise from:

a. Sudden loss of a generating station

b. Sudden addition of load

c. Sudden loss of one or more multiple transmission lines

d. Major system short circuits

In fact, it was quite generally expected that the power limit for such transient conditions would be less than the steady-state pull-out power.

However, very complete analytical studies, verified by thorough tests on the miniature system used for the steady-state power-limit investigations previously discussed, have largely dispelled the doubts of successful operation of extensive power systems under heavy load transients. Briefly, the following important conclusions have been reached from the evidence furnished by analysis, miniature-system tests, and field experience.

1. The power limit of a system, when load is suddenly applied to some element in that system, is the same as the pull-out power for slowly-applied loads, provided conditions of excitation and voltage are the same for the two cases. Certain transitory phenomena, discussed later, so affect system stability that *the fundamental criterion of stability appears to be the steady-state power limit.*

2. Power oscillations during a transient-state induced by the sudden application of load will not be excessive with units of comparable rating at the various points on the system. With an infinite generating unit, or an extremely large system interconnected with a relatively small one, the power "overshoot" may approach 100 per cent of the load increment.

3. Maintenance of stability during short circuits is mainly a matter of adequate relaying as duration of the short circuit is probably the most important single factor entering the problem.

During the existence of a transient state caused by a sudden change of load or a short circuit, a number of factors come into play which do not appear in steady state operation. Among others, there are the kinetic energy of machines, the time element of electromagnetic circuits, as in excitation systems, and the load-time characteristic of prime-mover governors. For these reasons, the calculation of transient problems is much more involved than the computation of steady-state stability. However, rigorous mathematical methods and step-by-step analysis[5] can be applied to the simplest cases. The analysis of systems of any degree of complexity becomes almost hopelessly involved so that resort must be had to the equivalent-circuit idea[6], which is extremely useful for the study of transients involving loads below the steady-state power limit.

Effect of Suddenly Applied Loads. Inasmuch as the basic purpose of the transient studies undertaken by the authors and other interested engineers was the determination of the relation between steady-state and transient stability, and the factor affecting the latter, the miniature system previously described was utilized. It was possible to simulate the sudden loss of a generating station by opening the oil switch tying a generating unit to the system; the sudden addition of shaft load by

closing a switch throwing a water-rheostat load on the d-c. generator coupled to a synchronous motor at the receiver end of a system; the sudden addition of "resistance" load by switching a dead resistance load directly onto the system; and the sudden loss of one or more multiple transmission lines by opening the oil switch in one of two 250-mi. *L-R* lines connecting a 225-kv-a. generator to a synchronous motor of identical rating.

The steady-state power limit of any particular system studied was first obtained for various constant-voltage or constant-excitation conditions. Then, by means of repeated trials, it was possible to determine how much load could be suddenly added to the system without causing loss of synchronism,—instability. The results were tabulated for the various cases and, as mentioned, on analysis revealed the important fact that the power limit for transient state was essentially the same as that for steady state, under the same conditions of excitation or voltage.

It will readily be apparent from what has been said that any time delay in the various elements making up a system would play an important part in transient stability. There are two such elements:

1. The electromagnetic circuits
2. The prime-mover governors

As the first is quite fully discussed later, only the second will be considered here. Inasmuch as governors are relatively sluggish in action, it may be several seconds after a disturbance occurs before the governors of a system assume their new positions. Consequently, in analysis of what happens during the first moment or two, constant flow (of water, or steam) is commonly assumed.

Short Circuits. Load transients apparently do not decrease the power limit of a system but the transient conditions obtaining during a major system short circuit radically affect stability. Not only do the inertias of machines and the time elements of governors and excitation systems come into play, but also the isolating effect of the short circuit. That is, no power flow can take place past the point of short circuit in the phases affected. For this reason, if the fault is not quickly cleared, a three-phase short circuit is likely to result in instability. Single-phase short circuits, whether line-to-line or line-to-neutral, are not so serious, inasmuch as partial flow of power is possible.

Brief consideration of what takes place in a system during a short-circuit disturbance may be illuminating. Assume a straightaway transmission with a single-phase line-to-line short circuit at the midpoint.

Just prior to the occurrence of the short circuit, the machine rotors will have a definite space-phase relationship fixed by the constants of the system, the load and the voltage. The instant the disturbance occurs the transfer of power between the machines changes, ceasing entirely in the faulty phase, and the rotors commence to assume a new relative position in space, depending on load and voltage conditions prior to the short circuit, the power flow, and the governor characteristics. Consider the generator. If the torque exerted by the system remains at the same value as previously, the net effect on the generator during the first instant will be zero. However, as the net flux is reduced and, hence, the voltage, this torque is likewise reduced and the machine accelerates, assuming no action on the part of the governor. Should the governor act, this acceleration will be reduced. The rate of change of net flux will be rapid in the first few instants, gradually decreasing with increasing time. This, of course, assumes no action on the part of the regulator tending to change the field ampere-turn loading. Should the torque imposed by short-circuit conditions be initially less than the load torque, the acceleration of the generator will, necessarily, be greater. It is evident, then, that the speed, the space-phase relationship of the generator relative to the initial position, and the magnitude of the net flux, (hence, terminal voltage) are functions of the duration of the short circuit.

Inasmuch as similar conditions hold for the receiver-end synchronous apparatus, it is apparent that *the essential factor for maintenance of system stability during short-circuit disturbances is adequately fast relaying.* Experience with actual systems has amply justified this statement.

Experience on existing systems, tests and conservative calculations indicate that major system short circuits are the severest type of transient. Only by very fast relaying can stability be maintained for powers near the steady-state power limit.

Effect of the Excitation-System Time Element on Transient Stability. In the discussion of system stability under suddenly applied loads, it has been said that certain factors so strengthen or stiffen the system that it is inherently stable for any load up to the steady-state power limit. What are these factors?

Undoubtedly, the most important element in the *temporary stiffening* of a system during a disturbance is the *field transient.* Due to the inherent relationship between field and armature circuits, the magnetic flux linked with an alternator field cannot change in the first moment following the sudden addition of load.[12] The increased armature current induces a field m. m. f. tending to sustain a constant flux linkage. If there is no automatic device increasing the exciter voltage, the flux will gradually die down to a new steady-state condition. However, and this is the important point, *during the transient, the machine reactance is less than the synchronous reactance.* Initially, following the sudden application of load or short circuit, the transient reactance[13] is effective, and this gradually increases

12. "*A Simplified Method of Analyzing Short-Circuit Problems,*" by R. E. Doherty, TRANS. A. I. E. E., Vol. 42, 1923, p. 841.

13. The transient reactance includes both armature and field leakage reactance.

to the steady-state synchronous value. Furthermore, the inherent stiffening of the system enables the regulator to act, causing the exciter to build up. Briefly, it is a race between the rate at which the system assumes the new load and the rate at which the excitation can build up. Now, the period of oscillation of a system is of the order of one second, and, hence, the first power peak occurs in a half-second. The *field transient*, or the transient reactance, stiffens the system sufficiently to meet this condition. By the time the power peak occurs again, the excitation system has

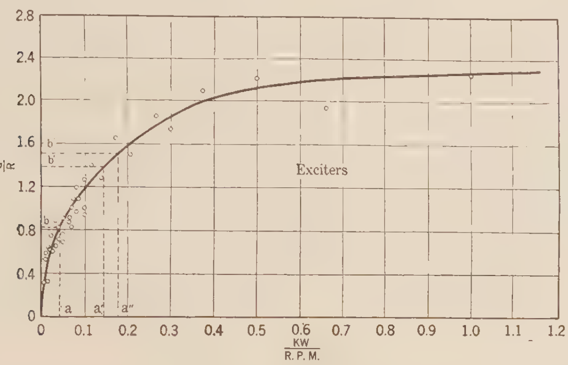

Fig. 6—Curve Indicating the Relation between the Time Constant and the Speed and Rating of Exciters

had considerable time in which to build up. In this respect, it will be interesting to note the relationship of the time constant $\left(\frac{L}{R}\right)$ to the volume of the exciter. Values for a large number of exciters, of different types and ratings, have been plotted in Fig. 6. In this case, the measure of volume used has been kilowatt per rev. per min., as this represents volume, for given current and magnetic densities. The actual exciters used in the experimental investigations are indicated by the points (ba), $(b'a')$, and $(b''a'')$.

It will be apparent that any scheme by which the resistance of the excitation circuit—that is, alternator field and exciter armature—can be reduced will tend to maintain constant flux linkages and so give the exciter a chance to build up. One method of accomplishing this would be the introduction of a *negative* resistance in the field circuit. A series exciter does function as a negative resistance. Its use in such a case has already been described.[3]

Neither the voltage regulator nor the series exciter, however, accomplish the primary object of the ideal regulation scheme—*i. e.,* the effective neutralization of armature reaction at the time it occurs. As previously pointed out, the mercury-arc rectifier, as an adjunct in excitation systems, does accomplish, to a large degree, this purpose, and in so doing, very materially stiffens any system so equipped, both in transient and steady states.

The inherent field transient so stiffens the average system that ordinary regulators and exciters are sufficiently responsive to maintain stability under heavy load transients. Mercury-arc rectifiers, or other devices accomplishing the same purpose, appear to be the most effective of all regulation schemes in reducing the effect of transients.

Conclusions

The preceding discussion has made it evident that the problem of stability is not confined to long-distance high-tension transmission lines, where economical considerations require operation close to the power limit. With the growth of the nation's power systems into widespread interconnected networks, and the consequent transmission of larger and larger blocks of power over short interstation tie lines, the problem of stability becomes vitally important, inasmuch as such short tie lines, on which depends reliability of service, may be operated too close to the power limit, with danger of instability.

In general, the investigations discussed have been most gratifying because they have indicated in what direction engineers interested in the design and operation of power systems should look for improvement. Furthermore, they have indicated that the real advances in obtaining additional stability lie in the application of certain types of apparatus—namely, devices for voltage regulation which fulfill the conditions of the ideal voltage-regulation scheme—*i. e.,* $\frac{dE}{dP} = 0$.

Improvement may be effected by changes in design of present synchronous apparatus—such as lengthening the air-gap or operating the pole structures at high magnetic densities.

To summarize, then, the following important conclusions have been reached from the studies undertaken by the authors:

1. The characteristics of synchronous terminal apparatus are of great importance in their effect on power-system stability. In fact, they may be of greater importance than the transmission-line characteristics.

2. Automatic voltage regulators and suitable exciters are essential to obtain, under all conditions, the same power limit as could be obtained with manual control and slowly applied loads.

3. The charging kv-a. of long transmission lines and extensive cable networks exercises more of a detrimental effect on stability than has been hitherto appreciated.

4. Improvements in system stability can be readily made by modifications of present designs of apparatus. Investigations indicate that real advances in stability come from the adoption of methods of voltage regulation having inherent characteristics close to those of the

TABLE III

POWER LIMITS FOR SYSTEMS WITH SHUNT REACTORS

System	Supply-End Reactor		Receiver-End Reactor		Excitation —Amperes		Initial Conditions		Power Limits—Kw.	
	Type	Ohms	Type	Ohms	Gen-erator	Motor	Volts	Kw. Motor Input	Calcu-lated	Test
1. Alternator, 500-mi. L-R line, motor....................	Saturated	29.2*	——	——	9.9	4.8	2300	0	—	84
2. Alternator, 250-mi. L-R line, motor....................	Unsaturated	58.4	——	——	7.1	4.75	"	0	—	99
	"	"	——	——	7.15	5.2	"	50	—	111
	"	"	——	——	7.7	6.0	"	100	—	130
3. Alternator, 250-mi. L-R line, motor....................	"	"	Unsaturated	58.4	7.3	7.35	"	0	105	118
4. Alternator, 250-mi. L-R line, motor....................	"	29.2	——	——	4.7	4.7	—	0	—	62
	"	"	——	——	10.1	4.7	2300	0	108	108
	"	"	——	——	9.8	5.1	"	50	—	113
	"	"	——	——	10.3	5.9	"	100	—	132
5. Alternator, 250-mi. L-R line, motor....................	Saturated	29.2	——	——	2.15	2.	—	0	—	21
	"	"	——	——	9.55	4.8	2300	0	111	119
	"	"	——	——	10.2	5.1	"	50	—	135
	"	"	——	——	11.0	5.9	"	100	—	152
6. Alternator, 250-mi. L-R line, motor....................	"	29.2	Unsaturated	29.2	9.9	10.0	"	0	—	146
	Saturated	29.2	Unsaturated	29.2	9.95	10.3	2300	50	—	154
	"	"	"	"	10.8	10.8	"	100	—	165

* The saturated reactor has a reactance of 29.2 ohms at 2300 volts.

ideal—*i. e.*, $\frac{dE}{dP} = 0$. One method studied—the mercury-arc rectifier as an adjunct in the excitation circuits of synchronous equipment in shop tests—showed real advantages.

5. The criterion of stability under all methods of load application appears to be the steady-state power limit.

6. To ensure stability during short-circuit disturbances, a well-designed and adequately fast relaying system is essential.

7. Results of good engineering accuracy can be obtained in the computation of system steady-state power limits by the application of available methods of calculation, although in the more complicated cases resort must be had to solution by the a-c. miniature system.

Discussion at Midwinter Convention

PAPERS ON TRANSMISSION STABILITY

(Nickle and Lawton, Clarke[1], Wilkins[2], Evans and Wagner[3])

New York, N. Y., February 8, 1926

R. D. Evans: Miss Clarke's paper dealing with the use of equivalent circuits for analyzing static stability, is of very considerable interest. Probably the most important contribution in the paper is the method of using an equivalent circuit to obtain the angle between generator and motor for maximum power. I believe this general method will find extensive use.

In carrying out the calculations, Miss Clarke replaces a complicated network with shunt admittances, by an equivalent network of a single series impedance, but with equivalent supply and receiver voltages. Sometime ago we had occasion to solve a transmission network in which many of the branches involved a long transmission line, and this led to a somewhat similar method of calculation. It is not convenient to go into the mathematical analysis at this time, but in the written discussion, we will submit an alternative proof of the method of using equivalent networks and equivalent voltages, which method is based on the use of general circuit constants and is of very simple form. I might say that some of the formulas used by Miss Clarke have been independently derived by us and that, for example, the transformation of the general network to the equivalent pi and vice versa, will appear in the revision of the "Electrical Characteristics of Transmission Circuits" by William Nesbit, which is now in press.

On the middle of the first page, Miss Clarke states that she takes the characteristics of synchronous machines into account by assuming a definite value of synchronous impedance and a definite value of excitation voltage. These assumptions are used to determine the static stability limit. These assumptions apply when the excitation is fixed but do not apply when the excitation varies under the control of automatic voltage regulator.

The determination of the proper method of representing synchronous machines for the calculation of static limits is beyond the scope of Miss Clarke's paper, but since it affects the static limit, it seems pertinent to comment upon this phase of the problem. The methods described by Miss Clarke are not applicable to the determination of the effects of voltage regulators since they do not permit the analysis of the time variation in excitation and of rotor movement. In the paper by Evans and Wagner, it is pointed out that the use of automatic regulators will actually increase the static limit over the value obtainable under

1. A. I. E. E. Journal, April, 1926, p. 365.
2. A. I. E. E. Journal, February, 1926. p. 142.
3. A. I. E. E. Journal, April, 1926, p. 374.

hand control. These considerations do not destroy the usefulness of Miss Clarke's methods which apply for hand regulated system. The methods may also be of value for systems with automatic voltage regulator in case an assumption can be made as to a definite value of machine impedance and a definite value of machine voltage. For example, if the regulator were fast enough to maintain terminal voltage, then machine impedance could be neglected, or if the regulator were merely fast enough to maintain constant flux then leakage reactance should be used. The true static limit would be determined, however, by a transient analysis in the manner indicated in the Evans and Wagner paper.

(By letter): In the verbal discussion, it was not practical to go into a mathematical derivation of an alternative proof for the method of equivalent networks given in Miss Clarke's paper. This derivation follows:

Referring to Fig. 1, the general equations for this network maybe written as follows:

$$E_s = A\,E_r + B\,I_r \tag{1}$$

$$I_s = C\,E_r + D\,I_r \tag{2}$$

where the notation for voltages and currents are indicated in Fig. 1 and A, B, C, and D are the general circuit constants. Following the notation used in the paper, complex quantities will be understood without any designating mark but a conjugate will be indicated by a bar over the symbol.

Let us divide equation (1) and multiply Equation (2) by the circuit constant A which gives:

$$\frac{E_s}{A} = E_r + \frac{B}{A}\,I_r \tag{3}$$

$$A\,I_s = A\,C\,E_r + A\,D\,I_r \tag{4}$$

Consideration of the above equations will show that they

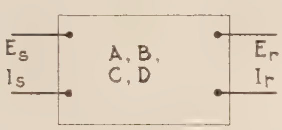

FIG. 1

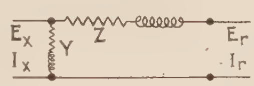

FIG. 2

FIG. 1—GENERAL NETWORK
FIG. 2—SIMPLIFIED NETWORK

correspond to the network shown in Fig. 2 below. The equations for the network of Fig. 2 are as follows:

$$E_x = E_r + Z\,I_r \tag{5}$$

$$I_x = Y\,E_r + (1 + Y\,Z)\,I_r \tag{6}$$

By comparing equations (5) and (6) with equations (3) and (4), it will be seen that:

$$E_x = \frac{E_s}{A} \text{ and } I_x = A\,I_s$$

Also

$$Z = \frac{B}{A} \text{ and } Y = A\,C$$

These considerations show that any network with constant impedance branches may be replaced by the network of the form shown in Fig. 2, using an equivalent supply voltage. It will be clear that the conditions at the receiver end for the equivalent network are identical with the conditions at the receiver end actual network. At the supply end, however, the voltage should be divided by A and the current multiplied by A. This simplification is obtained by the use of a transformation constant A, which constant is a complex number and necessitates a phase shift correction for power quantities as indicated below.

$$P_x + j\,Q_x = E_x\,\bar{I}_x = \frac{E_s}{A}\,\delta\,\bar{A}\,\bar{I}_s = \frac{\bar{A}}{A}\,E_s\,\bar{I}_s$$

By consideration of the simplified network of Fig. 2, it is possible to obtain the receiver power and the corresponding angle between supply and receiver voltages by consideration of only the series impedance Z and the phase shift in the equivalent supply voltage from the equivalent network.

Of course, the actual network might be divided in such a way as to permit the use of equivalent voltages at either end of the actual network.

We wish to emphasize the simple manner here employed to find an equivalent network which consists merely in rewriting the equations of the general network in the desired simplified form, and finding the equivalent network that corresponds thereto. The above method has been employed on a few occasions, but the phase shift introduced by the use of the equivalent voltage has been found to be somewhat confusing. The actual limiting angles between supply and receiver voltages may be computed directly from the general circuit constants for the over-all network, and the power corresponding to the limiting angle may be obtained graphically as is brought out in the accompanying discussion by Mr. Wagner.

H. W. Smith: A cursory review of Miss Clarke's and Mr. Nickle's papers indicates that methods are now available for the calculation of the steady-state power limit. These methods substantially agree for all practical purposes. Mr. Nickel's paper conveys the impression that the criterion of stability is the steady-state power limit although on the sixteenth page of his paper, tests are mentioned in which a dead single-phase, line-to-line short circuit, continued for half a second, reduces the power limit to 31 per cent of the steady-state power limit.

I think that all operating men will agree that if this is true, over-emphasis has been placed on the steady-state power limit. In any actual operating system, even though the best known relaying system is utilized, faults will occur, and on high-voltage systems they cannot be cleared in less than one-half second. It thus appears that the study of stability under fault conditions is extremely important.

Mr. Evans' and Mr. Wagner's paper is an extremely valuable contribution. They have developed a method of analysis of stability applied to an extensive transmission system, and this has been checked against actual tests which have been described in Mr. Wilkins' paper. The close agreement between the calculated results and test results seems to indicate that the method of analysis and assumptions made are correct enough for all practical cases. This paper indicates that for fault conditions, the transient stability is less than the steady-state limit. It would be very convenient if we could express this in terms of per cent of the steady-state power limit. This, however, can not be done, and for each system it will be necessary to determine the transient stability by a method of analysis indicated in Mr. Evans' paper.

In deciding on the limit to which systems can be worked the service standards must be considered. It may be permissible to have a system pull out of step under a fault condition that may occur at rare intervals, but if operation must be satisfactory for all fault conditions, the power limit must be considerably less than the steady-state limit.

H. H. Dewey: The general problem of power limits of transmission systems or stability has been before us only for the last year or two actively, and the papers that have been presented so far have left the subject in a somewhat confused state.

The problem as a whole is one that is assuming greater importance, as Mr. Wilkins points out, due to the interconnection of our power systems and the fact that we are endeavoring to make more use of our transmission lines. When we actively started the study of what limitations were important and what to do about it, we naturally started in a number of different directions and there was no very concerted effort made to direct our investigations along the lines that would produce immediate results.

The investigations that were made by the manufacturing companies with their artificial lines brought about certain basic results that were of immense importance. We found out things that we could have easily calculated if we had taken time enough and had got the idea but in our artificial transmission systems these suggestions came up as we noted the results of our tests.

When we had the first papers on this subject at Philadelphia two years ago, practically all of the authors, and I believe most of the men who discussed the papers, were willing to concede that stability depended very greatly on the excitation of our synchronous machines. They were also willing to concede that there was not very much hope of doing anything with our regulators or with artificial changes that could be made in the excitation during a transient. Starting out with that as a basis, we reached limitations of transmission that were surprisingly low. We found that it was difficult to get full rated output out of a generator when its excitation was limited by that necessary to produce normal terminal voltage under the conditions with which we started. That is one point that we come to a conclusion on on our artificial transmission tests that regulators were of extreme importance, and that due to certain facts such as the time element required to put on additional load or the rate at which transients come on, we could make use of artificial regulators and could thus increase the stability of a generator or a generator and its transmission line including transformers and all of the circuits in between.

So that, we feel, is an important point that we have fairly well settled on and I believe that the investigators fairly well agree that artificial regulation is possible and important.

There are a number of things that come before us in the study, some of which make us revamp some of our ideas on transmission. One point that I have voiced a few times and have been questioned on is the effect of charging current, the effect of capacity in our transmission line. It is in effect an absolute detriment. We have always in the past been in the habit of thinking that a long line introduced extra reactance and it was a bad thing to introduce such reactance and cause a voltage drop. We have felt it was compensated for by charging current of the line which had a tendency to hold up the voltage. That is true so far as regulation under specific conditions is concerned but when we are trying to get the last drop out of the transmission system from the generator to the motor, if there is any charging current in between, that current reduces the excitation required on the generator and the excitation required for the synchronous load and it is an absolute detriment, therefore, because it reduces excitation and decreases the maximum power that can be transmitted. That is a point we dislike to give up but it is there just the same.

I was very much interested in Mr. Wilkins' paper on the test on a practical transmission system and fully agree with him in his statement that artificial transmission systems are of some use in studying the problem but the proof of the pudding is in the eating and we must apply our studies to a practical system and the points that have to be taken into consideration are so many and varied that we cannot reproduce them on an artificial system. We can get the basic principles, however, and those basic principles have been fairly well settled on by our studies on artificial lines and we hope there will be many cases of analyses made such as that on the Pacific Gas and Electric Company's system. The more complicated the system, the more difficulty we are going to encounter in making such a study because there are so many side issues coming in,—points Mr. Wilkins brought out, such as the speed of the relays, the action of the governors, the characteristics of the particular machines you have and the complicated number of machines of varied characteristics.

There are certain things that we know will increase stability. We know that a generator having low reactance helps to increase stability. The characteristics of transformers and characteristics of transmission lines themselves must be taken into consideration. The problem is one we are just starting on and one that is worthy of the combined efforts of all of our best people who have the opportunity to study these problems.

In general, we have not felt that the stability problem is one that was bothering us to any great extent, but usually when we have trouble there are so many things happening that we do know about that we concentrate on the analysis and cure of those particular troubles, and if we knock the system out of step we think it is another happening and one we have let go. Since we have started to study this problem, we have found case after case of pure power limitations that a few years ago we should have passed over as being an incident rather than the real cause of our difficulty.

The main problem before us is the question of the effect of short circuits. It has been pointed out by the authors of the papers that steady-state stability is something that is fairly definite, something we can increase to some extent by careful design of our system and regulating equipment and so forth, but the problem of short circuits is one that we know very little about. We know that we ride through certain types of short circuits. We know that other types break up our system. The analysis of the difference between these varied kinds of short circuits is one that requires more data before we can come to definite conclusions.

On high-voltage lines, we are much more likely to have grounds than we are to have line-to-line short circuits and I believe that has been the history of the 220,000-volt systems in California and the study made of their short circuits last fall brought me to the conclusion that with reasonably fast relaying, we can ride through a ground. It is a pretty difficult thing, however, to run through a phase-to-phase short circuit.

Mr. Wilkins pointed out some of their experiences and on the Southern California System, I found they have had many more grounds on the high-tension line than Mr. Wilkins has had due to the different conditions, but their record of relaying and holding in step has been excellent during those times. But with short circuits on the 66,000-volt system which is veritable network, the short circuits are of the order of 1,000,000 kv-a. when they are phase-to-phase. They have had great difficulty in keeping the system in step. They have dropped out of step fifteen times from the first of January to the first of October. That is an extremely serious condition when the drop is a matter of 300,000-kw. loads during those times.

That, you probably will say, is poor operating but operation hasn't much to do with it; it is the limitations we are getting into in the big system where we get short circuits right in the center of the system.

H. H. Spencer: I think the electrical engineering profession should be most grateful to Miss Clarke for having reduced so complicated a problem to a slide rule and arithmetical basis from the more complicated methods which we have been assumed to use during the past two or three years that the problem has been confronting us. Perhaps the most obvious difference between Miss Clarke's method of calculation, and some of the other methods which have been presented, is her choice of a constant generator reactance. Other investigations have presented methods of analysis which take into account the variation in synchronous reactance in accordance with the Blondel or similar diagram. I think it would be most interesting if Miss Clarke would point out what method is used in the selection of this constant synchronous reactance.

Another point which is perhaps not entirely obvious in the equivalent circuit method of calculation is that it is possible for the receiver network to which a transmission line is tied, to fall out of step *per se*. That is to say, that although a transmission line feeding a network may of itself be stable, the network which is fed may go into instability by virtue of its connection with the transmission line. Just how that works out can be seen by looking at Miss Clarke's example No. 3 on the 11th page of her paper.

Suppose the receiver system had consisted of 100,000 kv-a. of

synchronous generators at the receiver end and these generators had been loaded not to 45,000-kw. but to a load approximating their rating, say, 80,000-kw., allowing 20,000 kw. for spare capacity. Under such a set-up, it is quite possible that line would be able to transmit the calculated load of 132,600 kw., but that a reduction in the voltage at the receiver end while not producing instability between the receiver load and the sending end generators, would produce instability between the synchronous load and the receiver end synchronous generators.

In regard to the difference between steady-state and transient power limits, methods of analysis are certainly developed at the present date to the point where given the same assumptions, two engineers will come out with the same answer. The difference between the answers which are obtained from transient stability analysis lies, I believe, in the difference in the fundamental assumptions in regard to the flux relationships in the synchronous apparatus at the two ends of the line.

Now the problem of flux relationships in synchronous apparatus is not one of novelty, but on the contrary is one which has been dealt with for a long time and with consistent success by designing engineers. It is necessary for the engineer who would calculate stability, or power limits, simply to compute the flux relationships which exist under certain known conditions by means of perfectly definite methods which are in common use. Having disposed of the problem of flux relationship, the difficulty of the stability problem very largely disappears and the power limits are readily calculable.

If we concede that during a particular transient disturbance the flux in a generator or a synchronous motor remains essentially unchanged, then I think any engineer would have a tendency to feel that the power of limitations imposed during operation under the conditions which led to the development of the initial flux would obtain throughout the disturbance. Thus switching operations such as the dropping of a generator or one of two parallel transmission circuits will introduce no power limitations below those imposed by steady state operation since disturbances of this sort have no tendency to reduce materially the flux in the synchronous generators. Short circuits, on the other hand, which do reduce the flux in the synchronous apparatus may very possibly impose power limits appreciably below these encountered in steady state operations.

Several single-phase, short-circuit analyses which have been studied during the past few months have shown that in a system of ordinary design, the steady-state stability limit is very markedly reduced by single-phase short circuits to ground. However, by means of changing the circuit set-ups, introducing a zero sequence reactance in the transformer windings, or using neutral reactors, the steady-state stability limit of the transmission system can be very closely approached.

H. K. Sels: In order that I may present clearly and concisely a number of points in some chronological order, I am taking the liberty of reading a prepared discussion. I do not wish to deal in personalities but to present such criticisms as I have from the purely abstract viewpoint of an operating engineer for a large and extensive system—particularly since the papers have not been in my hands long enough to fully acquaint myself with their respective contents. After three years of theoretical and experimental investigations I am more interested in the questions,—what has been accomplished and whither are we bound? No single organization seems to be responsible for the headway that is being made and I offer that as a hint to some of our several transmission committees.

The question of stability is as old as the alternating current art itself. We have always been confronted with the problems of synchronizing power between large generating stations, "hunting" of synchronous motors and the stability of rotary converters. A large number of papers have been presented before the Institute relating to these problems. The impression one gets from the papers which have been presented on the subject of stability is that we have discovered something radically new, some vital thing in which our power systems are unduly weak. Such is not the case and our methods of electric distribution are no weaker than they have been, by virtue of this discovery. However, what we do have that is new is a broader vision of the problem and the relation of its elements, and new methods of attack, and we hope, after all the facts have been analyzed, that we will obtain a solution which will extend the power limits of transmission to the ultimate.

Fundamentally, what we are really interested in is the power limits of a transmission system. A large number of factors determine the power limits of a system. It may be the current carrying capacity of the wire; it may be the economical amount of power that can be transmitted over a given line before it pays to build additional lines and maintain the same continuity of service, or it may be the question of stability of operation, which are the subjects of today's papers.

Psychologically I think it would be better for us to speak more in terms of the power limit, remembering that stability is only one of the important factors involved.

I believe everyone is over-emphasizing the relation of stability to high-voltage transmission. Of course it is true that stability is more likely to fall within the economic power limits of transmission at the higher voltages, but this does not reduce the importance of stability at all voltages and on all systems. Every operator is familiar with the losing of load or the dropping out of synchronous apparatus during system disturbances and fundamentally this is nothing more than the effect of instability. Therefore any improvements for stability apply equally well throughout the system.

Just to refresh my memory on the general trend of opinion on the various factors entering into the stability question, I reviewed recently all the papers and discussions that have been presented before the Institute. From an operating viewpoint I was very much impressed with the technicalities and, to me, the impractical viewpoints which were expressed. I believe that the average engineer would be hopelessly lost in attempting to follow through calculations on anything more than a very simple transmission system rather than a large interconnected system where the attempt is made to keep short circuits as low as possible by using synchronizing buses with reactors between individual generators and other complications used in the layout of the modern system for dispatching load; in fact it is very much like the mathematical conundrum of trying to solve a problem having more unknown variables than equations.

In addition to the factors outlined by the various authors, let me indicate for a moment some of the multitudinous conditions which the operating engineer must consider in making any calculations on stability. First, today we have a certain distribution of power stations serving a given load in a given territory connected up with a certain arrangement of transmission. Tomorrow we have a more efficient generating station coming into operation, a new arrangement of transmission to new load centers, which entirely alters the fabrication of the system. In actual operation the load conditions obtained hour by hour, day by day and year by year, change on account of the relative efficiency of the generating units on the system, the variation in load and different set-ups of lines in and out of service due either to failure or ordinary maintenance. All of these features only serve to make an intricate problem more involved. In attempting to determine a method of calculation which can be used with some degree of accuracy, I believe we should use those assumptions which we find agree the closest to actual operating tests.

Today's papers indicate more than ever that the methods of calculation used by the different engineers do not differ greatly in theory, but there does seem to be some difference of opinion as yet on the assumptions to be made and whether the steady state or the transient state is more important. These differences

apparently account for the divergence in the results of calculations by different engineers. As I have already brought out, the problem is so intricate that at best the solution is a cut and try process in which your methods of calculation and assumptions must conform with the results obtained by experience. For this reason I believe that for the present at least we shall consider all calculations only qualitatively and not accept calculations by separate engineers as comparative unless made on the basis of the same assumptions. For example, I might agree with the general shape and relationship of the curves in Fig. 17 in the paper by Messrs. Nickle and Lawton, but not agree with the maximum power scale due to some difference in my calculations.

With regard to the relative importance of steady-state and transient conditions, I believe it is evident that in cases dealing with high voltage, long distance transmission where the stability limit falls within the economic power limit of the line the steady state performance of the line will be of primary importance, because with such a large amount of capital tied up in the transmission system every means possible will be used to make failures on the transmission practically unknown. While the transient state does not enter so much into economics of transmission, it should be expected that continuity of service to local loads as well as the extreme importance of keeping a large high voltage system operating continuously as a whole will make this a factor not to be overlooked. In the case of lower voltage and shorter distance transmission, we can point to case after case of both major and minor importance in which some disintegration of the system takes place during a system short circuit. In actual operating experience I have yet to hear of the case where a system designed to operate in parallel has fallen apart due to steady-state conditions except where the static limit was reached in the Southern California Edison system within what we might say is the economic emergency capacity of the line. However, I should like to ask what experience shows here that transient stability is not an important factor. Before too much discussion is entered into on steady-state and transient stability, it would be apropos to have the terms defined, and we may find more of us in agreement than is apparent at first. Personally I classify the steady-state stability limit as that load which breaks down a system when slowly applied and the transient stability limit as that load which breaks down a system when suddenly applied or during switching operations including short circuits. It is conceivable that under certain conditions of small load increments or minor switching operations, the two limits will be the same when so defined. Summing up the relative importance of steady-state and transient stability, here again I believe we must resort to actual operating experience to tell us where our weaknesses lie. It is commended that the various investigators review the interruption records of some of the operating companies.

If we must rely so much upon actual operating experience, you may then ask, "What are we gaining by all our calculations?" As an operating engineer, I turn to the manufacturers of electrical equipment for the answer to this question. There is relatively little that can be done in changing the characteristics of our transmission systems so as to get more power per circuit over them, but there is apparently much that can be done in the development of terminal equipment. As already indicated, calculations are of more use as a qualitative measure than as a quantitative measure, particularly in reducing the annual bickering as to the relative merits of designing equipment.

There is a point to which I have been leading in this connection and that is as to whether the design engineers of terminal equipment are making its characteristics to suit special cases or whether the improvements are to take the form of a general design which will be suitable to meet the ever-changing conditions in a developing system. For example, I believe these improvements in design should be of a general nature because if we picture the developments of a twenty- to thirty-year period in a large interconnected system, the various load centers in the network will pass through a number of stages in which machine characteristics of only a general nature will apply. Of course for periods of a longer time, we can, by the usual methods of accounting, charge off old equipment and buy new of suitable character. If we take a broad vision of the problem at this time, however, we have an opportunity for obtaining economies which otherwise might be lost.

I should like to call your attention to the related problem of short circuits. Broadly speaking, a short circuit on a system is merely a certain type of load, of which the characteristics are rather elusive, but we can assume conditions covering a wide range in the hope of representing the actual conditions and apply the same methods of calculation carried out in studying stability. Here, then, we have a new method of investigating short circuits which takes into account the various phase relations of the prime movers, giving us a better picture of the duty required of our oil circuit breakers. From one standpoint we may be pessimistic in making calculations on the assumption that the sources feeding the short circuits are all in phase, but on the other hand I believe we have been optimistic in the way our circuit breakers have been performing in interrupting large short circuits, the value of which has been obtained from short-circuit calculation on the d-c. tables. It may seem somewhat unfair to add to the criticisms of our circuit breaker performance but it is a question which is closely allied to the stability problem. The whole thing is like burning the candle at both ends. On one side, we are trying to make our systems more stable which, in a sense, means greater concentrations of power and greater short circuits, and on the other we are trying to keep our concentrations of power to a minimum and thereby relieve our short circuit requirements. How can we have our cake and eat it? The only possibility in view along this line is to lay out small individual systems interconnecting them for diversity and reserve purposes only, but this step is in direct opposition to present tendencies in operating economies.

It is easy to sit here, and I may as well add, in our offices, luxuriously basking in the sunshine of a successful convention or conference, and dispose of this and that theoretical possibility with some oratorical gesture, but we must remember that experience often reverses the best of our intentions. I might illustrate this by an actual happening. The continuity of service on a given substation bus having two independent power station sources and two independent feeders from each of these was questioned and the statement was made that a shutdown was well nigh impossible. Approximately six hours later the impossible happened and the substation had an interruption measured in hours and the trouble was not a bus fault. We must remember that there are a number of links in the chain between our design tables and the distribution of power to the ultimate consumer. We are dependent upon Tommy Riley, Buck Jones, Ted Flinn and the rest of the boys on the firing line, who, in weather like this, keep maintenance on switching to the point where we may expect fast relaying. The more we can incorporate improvements in the inherent characteristics of the apparatus itself the more we will remove the personal element and for that reason we should proceed slowly in getting greater stability with additional equipment that may not function at the critical moment. It is easy to set up operating conditions but often quite another matter to obtain them. Therefore, I believe it is more practical and economical to first improve the characteristics of equipment now in general use and then turn to the possibility of adding other auxiliary equipment.

C. A. Powel: There are two points mentioned by Mr. Wilkins, and also by Messrs. Evans and Wagner, upon which I wish to comment. The first is the character of system oscillations at times of a fault to ground. Ordinarily, one thinks of a short circuit as reducing the energy output of a generator. How-

ever, in the case of a fault to ground on a large transmission system, the effect may be to actually increase the generator power output. This is due to the resistance in the ground connections from the faulty conductor to the transformer neutral.

Three records have come to my notice, and in each of these cases the generator output was actually increased, and in two of them the prime mover input was also increased by the opening of the gates. While this evidence should not be construed as meaning that all faults to ground will increase the power output of generators, it certainly does substantiate the position which has been taken that the resistance of faults to ground must be carefully considered.

The second point is the fact brought out that there is no particular value for the transient limit of a transmission system. Loss of synchronism at times of fault is dependent not only upon the system layout, but also on the load being carried and on certain speculative elements as to location and character of the fault. The point seems to me important, because it involves the whole question of rating of transmission systems. If the operation is such that it is permissible to pull apart every time a fault occurs, then obviously it will be possible to carry a load not far from the static limit. If, however, the transmission system is expected to ride through the majority of troubles, the power transmitted must be kept considerably lower.

In view of these considerations, it is desirable to obtain data

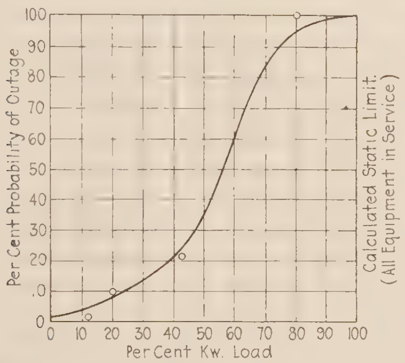

Fig. 3—Probability of Outage of Transmission System as a Function of Load in Case of Fault

as to outages and to plot the results in the form of a probable outage curve as a function of the load. Such a curve is shown in Fig. 3. All faults on the transmission line, and in addition, faults on secondary systems which produce outages, should be considered. It will be noted that the curve shows a definite but small probability of outage when the system is carrying zero load; such outage, for example, might be due to an operating error. The curve also approaches 100 per cent outage as an asymptote at the static limit. It becomes very steep in the middle portion.

The smooth curve which has been drawn is based on the limited amount of data which has been obtained for a particular system. While more complete data will probably change the exact points through which the curve would pass, it will not change its general shape.

The shape of the load curve on the transmission system must also affect its rating. If the power transmitted varies so that its peak value is only of short duration, the maximum rating can be kept higher with the same risk of outage, because the probability of faults is independent of the load.

Stability and not the losses in the lines determines the rating of a transmission system. Increasing the size of conductors will not appreciably increase the stability, and consequently the question of rating is of prime importance when deciding on the size of conductors to be used in a transmission system. The expenditure for extra heavy conductors may not always be justified.

R. E. Doherty: I think that the Institute is to be congratulated on having the papers which have been presented at this session, particularly the one of great importance, Mr. Wilkin's paper, which, for the first time, gives some actual operating data regarding these problems.

I should like to say a few words with respect to methods of calculations which have been referred to in various papers. A new subject, or a new phase of an old subject, came up recently, (within the last few years), and independent investigators attacked that problem. New nomenclature appeared, and each man has his own notion about those matters. Until they are standardized, we always shall have with us the well grounded objection of the next-to-the-last speaker, that he doesn't know what every one is talking about, and I gathered that he doubted whether the authors did. I have sympathy with his bewilderment.

Each one of us who studies this problem must make some simplifying assumptions. I think that there is one point on which we are all agreed; that a complicated power system network is not amenable to rigorous treatment by mathematical methods as we know them now, and I doubt that it ever will be. It is therefore necessary to make certain simplifying assumptions. Mr. A may make one assumption, Mr. B another assumption, and so on; but before he acts on it, you can rest assured that he is going to have some data or actual experience, some basis for his conclusion before he takes any step toward actually applying it. And if their conclusions on which action may be based are in substantial agreement, it seems of little avail, and certainly misleading, to publicly emphasize trifling disagreement of experts on certain details. While I may appear to be letting the cat out of the bag, so far as this apparent disagreement is concerned, I wish to state that when it comes down to brass tacks on a given proposition, to a study of some proposed system, the agreement among engineers seems to be pretty complete on what can be done and what cannot be done—which indicates to me that the more important factors are generally understood and agreed upon. I am sure all of you who are not daily living with this problem, would rather have those who are discuss and settle these disputed details over a table rather than here on the floor of the convention. I think one of the first things that could be settled in that way is nomenclature, and I propose that it should be done.

Just one word about this discussion of static stability and transient stability. I don't like to talk about stability. I share the view of a previous speaker, that "power limit" is a perfectly definite thing. It happens that the maximum power in some cases is also the limit of stability, but it is not in all cases. You can have a maximum power which is not the limit of stability, but I think all engineers are agreed on this: That there is a definite maximum power which can be transmitted over a given system under steady state at normal voltage. It is a perfectly definite thing, and everybody will agree on the value of that limit. And if so, let's talk about that limit.

We have found on investigation that if one throws on any load up to that limit, and the system is controlled by an ordinary vibrating commercial type regulator, the system will carry it. It will not lose synchronism. There may be such cases where synchronism would be lost, but we haven't found them. So long as the power to be carried is not greater than the static limit under the new condition—for instance, when a line section has been switched out—you can get away with it. In connection with this, I agree with the conditions mentioned at the top of page 2, second column, in the Evans and Wagner paper. The supposition is that if you have adequate relaying system and can promptly clear a line-to-ground fault, it is possible to carry through it.

In connection with this, Mr. Nickle states in his paper that

the static limit appears to be a criterion for the study or determination of power systems, and I submit that this is a reasonable position to take. It does not say that there are no other criteria, and that if it is satisfied, the system can not fall out of synchronism. It does say, however, that if it so happens, during a transition from condition A to condition B, the system is so regulated that it could carry condition B under steady state, then it can, by virtue of that regulation and the inherent electrical and mechanical characteristics of the synchronous machines, carry through the transition and remain in synchronism. Now if this were true in all cases, the steady-state limit for the worst condition B would be a comprehensive criterion. Our conclusion is that with proper regulation and, excluding short circuits, it would be generally true. It is probably true in the usual line-to-ground short circuit. However, whether or not we speak of the steady-state limit as a criterion, I earnestly submit that it is a definite figure which is characteristic of any given system, and is a quantity which any informed engineer with the same data will arrive at. It therefore constitutes a sort of a bench mark for reference.

I wish to add a word about high-speed excitation. Two elements are essential in an excitation system in order to increase the maximum power beyond the steady-state limit to which I have just referred. One is an exciter of sufficiently high magnetic speed. The other is an automatic regulator which would properly control the exciter. The high-speed exciter is easily obtained. However, no commercial regulator within our knowledge at the present time has the required characteristics to thus utilize such an exciter. The mercury-arc rectifier scheme[1] which was discussed at the Seattle Convention has the necessary inherent qualities. With proper regulator control there should be no discontinuity between the steady-state power limit obtained with the standard exciters as ordinarily regulated, and the limit obtained by the extremely high-speed excitation of the rectifier, so long as the increased exciter speed is properly applied. And while I reiterate that inherent characteristics of present day commercial vibrating regulators prevent their accomplishing this, it is nevertheless hoped that a regulator of proper characteristics may presently be available.

To sum up my discussion, it is certainly gratifying that all engineers who are studying these matters seem to be coming to the same general conception of this whole problem. There are certain trifling matters concerning which they are not yet in complete agreement because they have started out from slightly different bases, some thinking one assumption is more important than another. But these are not of general concern. The whole problem, I say, is sifting down to a narrower range in which we can all view it from the same angle and agree, provided we are careful about defining the terms we use.

C. L. Fortescue: I want to express my appreciation of the ingenious method Miss Clarke has developed to determine the static stability limit. I also wish to say, however, that the methods that have been used before are in reality no more complicated than Miss Clarke's method but the apparent simplicity of Miss Clarke's method is due largely to the able way in which it has been presented.

Regarding the paper by Messrs. Nickle and Lawton, I want to congratulate them upon this paper. It is an extremely readable paper. I want to emphasize in discussing this paper not the apparent differences in opinion between our group of papers and this one, but more the points on which we have come to an agreement. There is a tendency in discussions to pick out the points of disagreement and discuss them only. As a result of that, those who read the discussions say, as I heard Mr. Roper remark, "Well, we can't make head nor tail of this matter. Some say this is black and others say it is white." The static stability limit is a very definite limit. One might say it is an invariant of a given system. It is quite a definite value and can be determined without difficulty. I shall go Mr. Doherty one better and say the static stability limit as defined by constant excitation is one of the criteria of the stability of a system—not the criterion, but one of the criteria.

In connection with this static stability limit, in considering ways and means to raise this limit, we found with high speed automatic regulators we were able to get quite an appreciably larger amount of power over the circuit.

Now I am bringing out this point not to emphasize the point of difference, but because this artificial stability has an element of hope in it. If you can do it with a regulator today, you may be able to get a regulator that will do it still better tomorrow. You will surely be able to get more power over a given line tomorrow. Maybe the automatic regulator of special design will be the answer; maybe an inherent regulator scheme will be the answer. We don't know now, but one of these days we will know.

Now regarding the transient stability as one of the criteria of operation: I want to say that after reading over the conclusions in the paper I was rather struck by the fact that transient stability wasn't considered of great importance, but on reading over the paper itself, I found data presented there that led me to say that transient stability was just as much of a criterion as the static stability.

One statement in the paper, page 16, calls attention to single-phase faults and points out if the fault is removed instantaneously, the load can be carried right up to the stability limit. Now if you remove a fault instantaneously, you are doing exactly the same thing as if you cut out a section of line on a loaded transmission line instantaneously. And we know if you cut out sections of loaded lines, the effect on the load limit is very small, so I think that is the answer to that.

As a remedy, mention is made of quick operating relays; that is part of the remedy but we must go a step or two further than that. We must have quickly operating circuit breakers and we must have adequate voltage regulating systems, either high speed or inherent, and we may possibly have to help out with the governing system and also consider the effect of resistance of the fault. I wish to point this out because I myself reached somewhat different conclusions from those of the authors from the data they present in their paper. We can't say that one limit is more important than another limit. We have several limits. We have the static stability limit, and if you raise that, you also raise the transient stability limit as a general rule, so that we have several loopholes to follow in order to solve this problem.

As to methods of calculating transient stability, I may say that we have found it practical to calculate even relatively complicated systems by the point-by-point method. It is of course a long drawn out tedious method. There is no doubt a technique will be developed in the course of time to enable engineers to calculate power transients in more complicated types of systems. In other words, the present methods are cumbersome and long drawn out but they will be improved and perfected in the course of time.

We do not dissent from the opinion that a dynamic model may be evolved, but we insist that such a model must take into account the essential facts, the most outstanding of which is that the differential equation of the motion is not linear. The condition with which we are concerned in transient stability is that unless we get instantaneous removal of the fault, it does not permit of the use of approximately the linear form in analysis. In fact, the problem is similar to that of a pendulum and the difference between the two problems is the difference between the cycloidal pendulum and the simple pendulum, between the harmonic motion and the elliptical.

I bring this point up because I think Mr. Nickle in the course

1. *Fundamental Considerations of Power Limits of Transmission Systems*, by Doherty and Dewey, A. I. E. E. JOURNAL, October, 1925, p. 1045.

of time will undoubtedly get the right kind of dynamic model to find the answer to the problem in the proper terms.

As to the effect of machine characteristics, the importance of machine characteristics has been emphasized by the group of engineers to which I belong. Machines designed according to present practise must incorporate the necessary stiffness, to use the authors' term. This may be done by designing machines with lower synchronous impedance, that is, with long air-gaps or saturated poles. This applies to generators and synchronous condensers. In addition to this, we must have voltage regulators quickly responsive to changes in voltage.

An alternative method which may develop is the compensated machine which may be a generator or a condenser. Partial compensation in the case of a generator may be considered of advantage. Investigations on compensated machines are being carried out now and data is being obtained which will be available in due course.

In regard to the intermediate condenser, the authors have indicated a substantial gain with sufficient condenser capacity. While the capacity requirements as represented by them are large, it need not worry us as there is no doubt that in due time the right kind of machine which will give the desired results with smaller capacity will be developed.

W. P. Dobson: Mr. Wilkins evidently relied upon telephone signals to obtain simultaneous oscillograph records at widely separated stations. In 1912 and 1913 the writer, during an investigation of transients on 60- and 110-kv. systems, made use of an automatic attachment to an oscillograph to accomplish this result. The closing of a switch on the oscillograph table operated the high-tension breaker, the film-motor and shutter in proper sequence to obtain the desired record on the film. Circuit breakers in distant stations were connected to the oscillograph control by means of the system telephone circuits. It was possible to obtain records of transients of short duration on a standard 12-in. film and satisfactory records of transients of over one second's duration were obtained with a 42-in. film. The apparatus was designed by Professor H. W. Price of the University of Toronto and was used on the lines of the Toronto Power Co. and the Hydro-Electric Power Commission of Ontario over a period of 18 months. Several hundred records were taken with a negligible number of failures. It is believed that this was the first instance of the application of automatic control of an oscillograph for this purpose.

H. B. Dwight: On the 11th page of Miss Clarke's paper, there is a diagram in which leading reactive kv-a. are plotted downward. This is typical of the papers by several authors. There is also a group of writers who draw this type of diagram with leading reactive kv-a. plotted upward, the same way that leading reactive current would be plotted. It is an inconvenience to have these two opposite methods in use, and as diagrams of kw. and reactive kv-a. are of somewhat frequent occurrence for various purposes, it seems that the time has come when it is appropriate for the Institute to give a decision as to whether leading reactive kv-a. should be considered positive or negative, and should be plotted upward or downward in diagrams.

J. W. Legg: Mr. Wilkins deserves much credit for recognizing the value of reliable high-speed records, and for insisting on having apparatus capable of giving reliable graphs at these high speeds. The Esterline graphic instruments used in these tests were too sluggish of movement to warrant a high-speed chart until they were reconstructed with greatly increased restoring torque and more than 50 times normal power input. This necessitated a battery of special transformers and special switching schemes to throw the graphic instruments out of the circuit after operating less than half a minute, to prevent excessive heating.

In 1914, while still a student, the writer conceived a truly portable oscillograph to operate with a low-voltage incandescent lamp, and to have wattmeter elements, and other effective-value elements, as well as the standard elements for instantaneous values. The ease of obtaining truly high-speed graphs, freely crossing one another, appealed to the writer as being worth the inconvenience of photographic development. A daylight-loading film holder was conceived then but not developed and perfected until 1921. In spite of this improvement in film-holders, all effort was expended to develop high-speed graphic instruments requiring no photographic film. Progress has been made in this line, but the demand for higher and higher speed records (with correspondingly higher-speed movements) has surpassed all improvements in standard graphic instruments. This is shown very clearly in Mr. Wilkins' paper. The standard high-speed (so-called) graphic instruments were of practically no value for these important tests until remodelled and forced at fifty times normal input. C. F. Wagner saw the limitations of these instruments, after all the improvements he had made, and made up several oscillographic wattmeters to be placed inside our standard, portable oscillographs, and in separate cabinets using standard oscillograph lamps, lenses, film holders, etc. These confirmed the writer's predictions and proved very successful in these tests.

Several years ago the writer figured on an instantaneous, polyphase, reflecting, wattmeter-element, with a natural period of approximately 2000 cycles per second. A single-phase wattmeter element, with a natural period of 5000 cycles per second, would be very simple, but not particularly valuable on account of the high (double) frequency oscillation of the power wave on a-c. lines. The quick-acting (but not instantaneous) elements, pushed through for these tests, proved so successful that they will be commercialized, in an improved form, very soon.

A nine-element portable oscillograph, considerably smaller than its three-element predecessor described in the JOURNAL of February 1923, has been designed to give nine simultaneous records on one 7-in. width of film. Three of these oscillograph elements may be replaced by high-speed wattmeter elements, or by other effective-value elements when they are developed. Such an instrument will be ideal for stability tests, and for operation on chance disturbances. A daylight-loading long-film holder has been developed to take films 6½ in. wide and either 3, 6, 8, 16, or 24 ft. long. Twenty-four-foot films were used for the first time in these stability tests, passing through in less than six seconds. For lower speeds the film-holder can be made to operate quite reliably for daylight-loading and daylight-unloading.

During the discussion of the writer's paper, in 1923, on "Expansion of Oscillography," J. R. Craighead seemed to doubt if the oscillograph could be made to function, automatically, quickly enough to show what happened before the oil circuit-breakers functioned. All that the writer claimed then, and more too, has been done since then. Our portable oscillographs have been set up in substations and have operated, repeatedly, on chance disturbances, and have given valuable information as to the disturbance and breaker operation. Furthermore the new single-element oscillograph (the OSISO) can be set up to record chance disturbances within less than one-thousandth of a second after the closing of a quick-acting relay. The 4-volt lamp is initially excited by a condenser charged to 110 volts, d-c. The lighting of the lamp is quick enough to obtain a perfect oscillogram of the chance rupture of the arc in a quick-acting circuit breaker on d-c. lines. With the proper quick-acting relay, operating on the steepness-of-wave-front principle, the oscillograph will function perfectly within two-thousandths of a second after the very start of a short circuit, before the quick-acting breaker can reduce the short-circuit current. The photographic film must be kept rotating all the time, for such extremely quick operation.

The advantages of such apparatus are being better and more universally recognized, and oscillography will continue to expand and be a greater and greater help to others besides the electrical manufacturer.

Svend Barfoed: In designing transmission systems to safely carry a specified load, I have in the past used methods that are very direct. They involve the use of diagrams in which the various factors affecting the power limit of a transmission system appear together and may thus be studied more easily. As yet I have not found any necessity for transmutation of the diagram and method into others which, as far as can be seen, are the exact equivalent. The accompanying diagrams illustrate such a study.

Fig. 4 has been described several times. The load lines are shown advancing by eights up to full load; to scale they are meas-

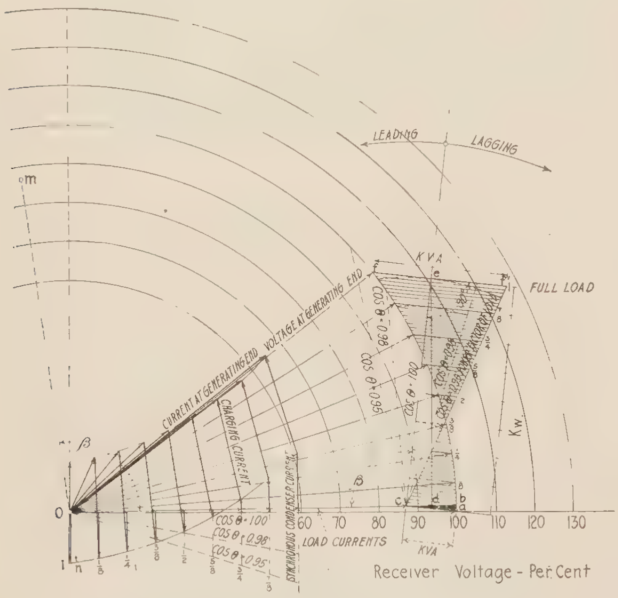

Fig. 4—Typical Regulation Diagram for High-Capacity Transmission Line

ured in position in kw. The magnetizing power is measured parallel to the load lines to the same scale in kv-a., being for example $c\,F$ at unity power factor of load at full load or $F'\,F$ at a power factor of 0.95. The magnetizing effect of the charging current is given by $a\,c$. Thus all factors affecting the trans-

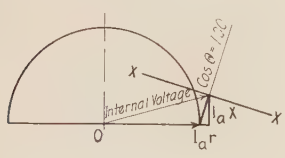

Fig 5

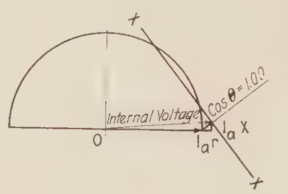

Fig. 6

Figs. 5-6—Generator Diagrams for Different Ratios $\dfrac{I\,r}{I\,X}$

mission limit of power of the line and transformers is had at a glance. It is at once apparent that all factors are very definite and do not admit of discussions of a qualitative nature. For any given relation the line and the transformers have characteristics which are fixed and quantitatively known. It can easily be seen that the smaller the resistance compared to a given reactance the higher the power limit, and highest for zero resistance. In other words, the more nearly vertical line $c\,e$ is, the higher the power limit. On the other hand, with nearly zero reactance the power limit would be very low indeed. The criterion is the tangency of a load line to any one of the circles shown on which it may be desired to operate. Tangency represents the static load transmission limit. Swinging the unity power-factor line $c\,e$ around c as center to the right, representing a designed decrease in reactance for the same resistance, makes

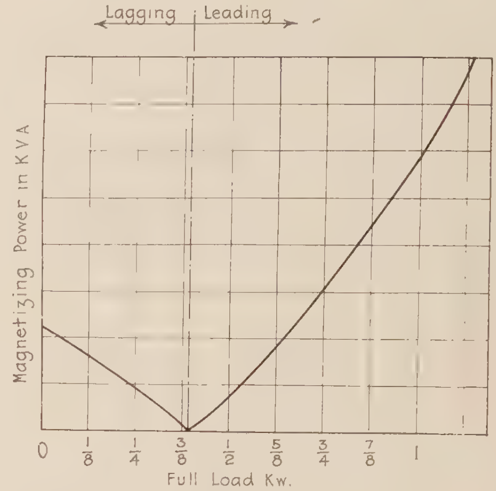

Fig. 7—Magnetizing Power Required from Synchronous Machines on System (From Diagram Similar to Fig. 4)

the maximum load lines become tangent to the circles at smaller and smaller loads and when finally the load lines become nearly vertical the ability of the system to transmit power almost vanishes. It is thus seen that in order to transmit power with alternating current the proper relation between resistance and reactance must prevail and it is evident that low resistance lines are highly desirable since the reactance of the line can be changed but little due to clearance limitations. Similar reasoning holds for the transformers, but with them it is also desirable that the reactances are no greater than required for the strength of the

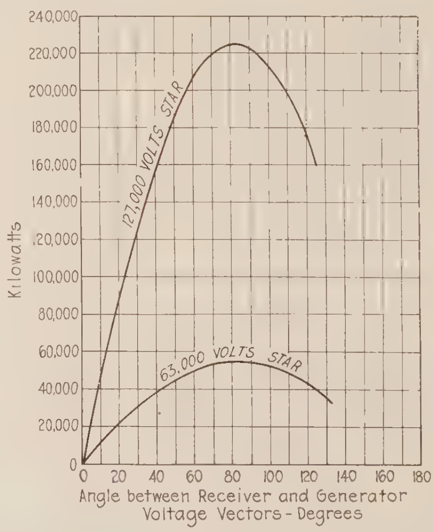

Fig. 8—Static Stability Curves—200 Miles of Line (Plotted from Diagrams Similar to Fig. 4)

mechanical structure during short circuit. At previous meetings when power transmission limits have been discussed, the characteristics of the synchronous machinery have been included, but in no very definite manner. It is with respect to the synchronous machines that it is ventured to hoist a warning signal. It is seldom that a large power plant contains but one machine. If there are several it is imperative that they have such character-

istics that they will operate properly in parallel under all conditions of load and can readily be synchronized. There must be no hunting between them. If for the sake of increased power transmission limit the synchronous reactance is very much reduced, hunting will surely occur between generators running in parallel in the same station, and stability, possibly, may only be secured again by adding reactors external to the machines. This is an old story and is visually shown in Figs. 5 and 6. In Fig. 7 the ratio $\frac{I_a r}{I_a x}$ permits the proper synchronizing force to develop between machines due to a large amount of power possible of transmission between them. In Fig. 6 the ratio $\frac{I_a r}{I_a x}$ is such that the limit to the synchronizing force is very quickly reached with the machines liable to fall out of step.

The effect of the load power factor is given at once by these diagrams, and there is nothing vague about the amount of magnetizing power required to compensate for power factor, either for voltage regulation or for a given power transmission limit. The synchronous condenser is a very admirable machine to give or consume magnetizing power in the required amount. It will perform exactly as desi ed if the V curve of zero power load coincides with the magnetizing power curve of Fig. 7.

From the above it is seen that the line and transformer characteristics and the charging current do not lend themselves to a discussion of power transmission limits. They are to be considered known and fixed within narrow limits. As long as we transmit power with alternating current, the charging current cannot be removed and to say that it is detrimental to a higher power limit is like saying that the current flowing in a coil of wire is undesirable because it heats the coil.

The power limit of a given transmission system is therefore influenced chiefly by the characteristics of synchronous apparatus. I accept the statement that the machine designers know how to design machines for maximum transmission of power. That being so, the transmission line designer would like to know in what manner this is done. He would like to know how the synchronous reactance is apportioned between self induction and armature reaction, how compensated for, whether means to affect a quick response to excitation power is counteracted by means to affect damping of power swings, and whether a machine designed for maximum power limit is a suitable machine for installation in a plant where there are several which must safely operate in parallel on the same bus bars.

It has been said that power factor has much to do with the power transmission limit. To be sure it has, but in a perfectly definite manner. Power factor lagging means that magnetizing power must be furnished by synchronous machines either at one end of the line or both; power factor leading means that magnetizing power must be absorbed by synchronous machines or by some other variable tractor. If the rate of change in magnetizing power is such that the excitation power of the field structures cannot follow at the same rate, oscillations will be started. Tests on actual systems cannot reveal much in this connection since the magnetic structures cannot be changed. Such tests belong on the test floors of the manufacturer. With machines of conventional design it appears that transmitting power at 220 kv. up to 250 mi. is safe when the lines are loaded to one ampere per 2200 cir. mils and condensers located only at the receiving end. This can be improved by suitable engineering of the line itself. A discussion of this would, however, lead too far at this time. Only this,—there must not be added further apparatus in power houses, substations or elsewhere until circuit breakers for 220-kv. operation have been improved to the point where they no longer constitute the present limit to transmission of power. The circuit breaker must perform its function without destroying itself too soon and it must open the circuit at such a rate that a power arc on the line will not have time to seriously injure the conductor. The circuit breaker must be relied upon to transfer without distress the energy from a line section in trouble to a parallel line. The normal energy to be transferred is of the order of 130,000 kw. It is comparatively easy to compute power swings and to provide a sufficient margin of safety. It is far more difficult to design economically a system where disturbances causing power oscillations will inherently be reduced to a minimum. The first problems to solve are 220-kv. circuit breakers and line insulation.

F. L. Lawton: It is certainly in order to compliment Mr. Wilkins and his associates on the courage and initiative displayed by them in attempting investigations of system stability on a power system of the magnitude described. Further, the addition of field tests of this type to the theoretical studies undertaken in the past few years affords an opportunity of passing judgment on the assumptions made in those studies.

It is indeed encouraging to note the real agreement between the conclusions reached by Mr. Wilkins and those presented by Mr. Nickle and myself, today, and also those in a recent paper[4].

The writer disagrees with Mr. Wilkin's observations anent the place filled by the use of artificial lines and miniature equipment. It is, of course, true that test data, whether obtained on an actual network or on miniature systems as used by Mr. Nickle and myself, apply only to specific conditions on given systems. However, and this is important, *it is virtually impossible to assign the right values to the factors affecting the stability of a real network*, of anything like the complexity of the Pacific Gas and Electric Co.'s transmission and distribution system. With the miniature system, methods of analysis can be studied, actual cases[5] checked, and *the methods of analysis may then be applied with real confidence in the soundness thereof to the solution of stability problems.* In this respect, the miniature systems with synchronous apparatus up to a few hundred kv-a. capacity have been of great assistance but it is not suggested that a 225-kv-a. system be used for the solution of stability—or rather, power limit—problems. For these there are available:

(a) The miniature system of Spencer and Hazen[6].
(b) The equivalent-circuit method of Nickle[7].
(c) Proven methods of computation.
(d) Experience.

When anyone conversant with the difficulties involved in analyzing system power limits by theoretical methods visualizes the physical data applying to the system in Fig.1, he will have a better appreciation of what a miniature-system method of stability analysis means.

When results of good engineering accuracy, directly applicable to proposed or existing power networks, can be obtained relatively easily and expeditiously by use of a miniature-system method and proved principles, it is presumed that they will be used and "actual quantitative values for this fundamental data" will *not* need to be "measured." Such miniature systems and principles, it would appear, are already available.

Regarding the contention that system stability, as a problem, is inextricably entangled with operating economics, this is largely true but, nevertheless, good progress can be made in determining the power limits of transmission systems under the majority of circumstances likely to arise.

The results obtained by Mr. Wilkins when the 220-kv. line at Pit No. 1 was switched out under a load of 24,000-kw. agree quite closely with those obtained by Mr. Nickle and the writer. I think that a little closer consideration will convince Mr. Wilkins that the cause of the greater disturbance on closing

4. *Fundamental Considerations of Power Limits.* R. E. Doherty and H. H. Dewey. A. I. E. E. Journal, October, 1925, p. 1045.

5. Such as the case described by H. A. Barre in the *Electric Journal* for June, 1925, and discussed by R. D. Evans, A. I. E. E. Journal, January, 1926, p. 70-71 and by R. E. Doherty, p. 75-76.

6. *The Artificial Representation of Power Systems.* H. H. Spencer and H. L. Hazen, A. I. E. E. Journal, Jan., 1925, p. 24.

7. *Oscillograph Solution of Electro-Mechanical Systems.* C. A. Nickle, A. I. E. E. Journal, Dec., 1925, p. 1277.

the line was entirely due to the effect of the line charging current in changing the phase and magnitude of the "open line" voltage relative to that on the generator side of the closing circuit breaker.

In connection with the above, it might be added that an oscillographic wattmeter with characteristics similar to that described was used throughout the major part of the miniature-system tests previously referred to.

To conclude, it appears that the first extensive investigation of power limits on an actual system of a fairly high degree of complexity leads to conclusions in substantial agreement with those presented by Mr. Nickle and myself, as well as others, entirely from the results of miniature-system studies, coupled with field experience and office analysis.

A. P. Mackerras: A pleasing feature of this paper is the use of graphical methods. Graphical solutions are usually sufficiently accurate for practical purposes; and, in addition to their rapidity, they give a better physical conception of the problem than algebraic formulas, and indicate more readily the effect of changes in the quantities involved.

In the construction of Fig. 3B, it has been pointed out that the locus of points at which $P\,Q$ subtends a constant angle is a circle with centre R. But it may also be of interest to note that the locus of points the distances of which from A and B are in a fixed ratio is also a circle. If the line $A\,B$ is divided internally at N and externally at N' in the given ratio E_A/E_B, this circle has $N\,N'$ for its diameter.

In Appendix C the equation

$$\text{Power} = \frac{1}{2}\,(E\,I + E\,\bar{I})$$

is given. The truth of this equation may readily be seen from the accompanying diagram. Let $O\,A$ be standard phase, and

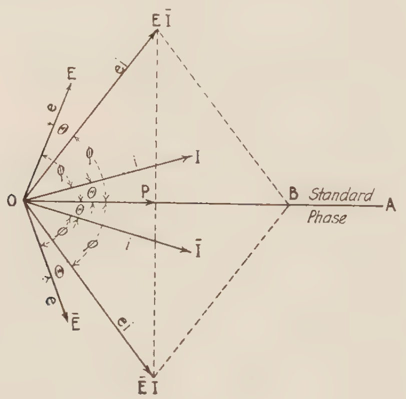

FIG. 9

let E and I be the voltage and current vectors the magnitudes of which are e and i. Then the conjugate vectors E and $\bar{I}$ will also have magnitudes of e and i, and their angles with $O\,A$ will be equal and opposite to those of E and I. To multiply the vector E by the vector I, we multiply their magnitudes and add (with due regard to sign) the angles they make with $O\,A$. The vector $E\,\bar{I}$ will therefore have a magnitude of $e\,i$ and will make an angle ϕ above $O\,A$, where ϕ is the angle between E and I. Similarly the vector $\bar{E}\,I$ will have a magnitude of $e\,i$ and make an angle ϕ below $O\,A$. Then clearly, the vector sum $\bar{E}\,I + E\,\bar{I}$ will be equal to $O\,B$, or $2\,e\,i\cos\phi$, which is twice the power in the circuit.

Sidney Withington (communicated after adjournment): Since the limit of power transmission is a function of the system frequency, it is entirely conceivable that in the transmission of large amounts of power over long distances it may be found desirable to adopt relatively lower frequencies than the standard 60 cycles; for instance 25 cycles or even lower. In this case there would be large frequency-changing substations at the centers of distribution. The frequency-changer sets might perform also the function of synchronous condensers, and the increment of cost would be relatively small compared to the total transmission line cost.

If this occurs and a low frequency is adopted for long distance transmission, it is entirely within the range of possibility that it would be economical for the electrified railroads of the country to obtain their power direct from these major transmission lines without the medium of rotary apparatus, perhaps balancing the load among the phases in sections. This is significant, considering the possibilities of railroad electrification, and may be a controlling factor in developing a standard system.

C. F. Wagner (communicated after adjournment): Miss Clarke has presented methods for the calculation of static stability for constant field current in a clear and concise manner. It should be noted in passing, however, that these limits do not represent the ultimate when automatic voltage regulators are used to maintain voltage. Miss Clarke uses the logical device of

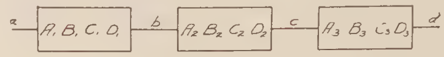

FIG. 10

representing loads where possible by static networks. This results in considerable simplification.

Using the various devices pointed out by Miss Clarke, the most general case in which the problem can still be reduced to a single synchronous machine at each end is that shown in Fig. 9, herewith, in which the three rectangles represent general networks, E_a and E_d the internal voltages and b and c the points at which the voltages are known.

Messrs. Evans and Sels in the July 1921 number of the *Electric Journal* have indicated how three general networks in series can be combined into one equivalent, so that the following expression is obtained.

$$\check{e}_a = \check{A}_0\,\check{e}_d + \check{B}_0\,\check{I}_d \tag{1}$$

where $\check{A}_0$ and $\check{B}_0$ are the general circuit constants for the three combined networks, $\check{e}_a$ and $\check{e}_d$ the star voltages at a and d respectively and $\check{I}_d$ the current at d.

Transposing equation (1)

$$\check{I}_d = \frac{1}{\check{B}_0}\,\check{e}_a - \frac{\check{A}_0}{\check{B}_0}\,\check{e}_d \tag{2}$$

The power at d

$$P_d + j\,Q_d = 3\,\check{e}_d\,\hat{I}_d = \frac{1}{\hat{B}_0}\,\hat{E}_a\,\check{E}_d - \frac{\hat{A}_0}{\hat{B}_0}\,E_d^2 \tag{3}$$

when E_a and E_d are phase volts at a and d respectively. Now let

$$\check{E}_d = E_d\,\epsilon^{j0} \text{ and } \check{E}_a = E_a\,\epsilon^{j\phi} \tag{4}$$

$$P_d + j\,Q_d = \frac{1}{\hat{B}_0}\,E_d\,E_a{}^{-j\phi} - \frac{\hat{A}_0}{\hat{B}_0}\,E_d^2 \tag{5}$$

The real component of the above expression P_d becomes a maximum when

$$\phi = \tan^{-1}\frac{b_0}{a_0}$$

where a_0 and b_0 are the components of $\check{B}_0 = a_0 + j\,b_0$. This determines the angle ϕ between a and d for which maximum power is delivered at d. It is necessary to calculate only the $\check{B}_0$ constant for the combined network.

$$\check{B}_0 = \check{A}_1\,(\check{B}_3\,\check{A}_2 + \check{D}_3\,\check{B}_2) + \check{B}_1\,(\check{B}_3\,\check{C}_2 + \check{D}_3\,\check{D}_2)$$

Having obtained the maximum over-all angle corresponding to maximum power delivered, the actual value of power delivered

can be determined by the following graphical means. From a knowledge of A_2, B_2, C_2, D_2 and the voltages at b and c, the sending and receiving-end power circle diagrams for the middle section can be drawn as shown by the heavy lines in Fig. 10. For any angle ϕ_2 between the voltages at b and c the power flow at these points is indicated by the points m and n. Every point such as m on the supply circle must also represent a point on a receiving circle for the first section. This latter circle is represented by the expression

$$P_b + j\,Q_b = \frac{1}{\hat{B}_1}\,E_a\,E_b\,\epsilon^{-j\phi_1} - \frac{\hat{A}_1}{\hat{B}_1}\,E_b^2$$

The center of this circle is located at $-\dfrac{\hat{A}_1}{\hat{B}_1}\,E_b^2$. It will be noted that all of these quantities are known and can be plotted at the point p. Now while the value of the voltage E_a is unknown (and incidentally will not be necessary to determine) the reference vector from which the angle ϕ_1 is measured can be drawn making an angle with the horizontal equal to that of $\dfrac{1}{\hat{B}_1}$ which angle is the same as the angle of $\check{B}_1$, *i. e.*, $\tan^{-1}\dfrac{b_1}{a_1}$ where $\check{B}_1 = a_1 + j\,b_1$. As stated previously, the point m must lie on the circle, therefore, and angle ϕ_1 between

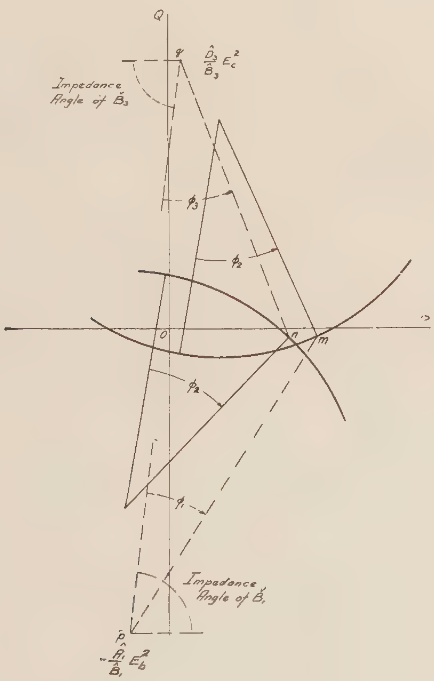

Fig. 11

$p\,m$ and the reference line indicates the angle between the voltages at a and b for the power transmitted at c corresponding to point n.

A similar construction applies to the receiving-end network. The power at c into this network is expressed

$$P_c + j\,Q_c = \frac{\hat{D}_3}{\check{B}_3}\,E_c^2 - \frac{1}{\hat{B}_3}\,E_c\,E_d\,\epsilon^{+j\phi_3}$$

The center of the circle q is determined by $\dfrac{\hat{D}_3}{\check{B}_3}\,E_c^2$ and the reference line makes an angle with the horizontal equal to that of $-\dfrac{1}{\hat{B}_3}$, *i. e.*, $\tan^{-1}\dfrac{b_3}{a_3}$ where $\check{B}_3 = a_3 + j\,b_3$.

The angle ϕ_3 between $n\,q$ and the reference line indicates the angle between the voltages at c and d. Therefore $\phi_1 + \phi_2 + \phi_3$ gives the total angle between the voltages at a and d for the power conditions at c corresponding to the point n. After a few

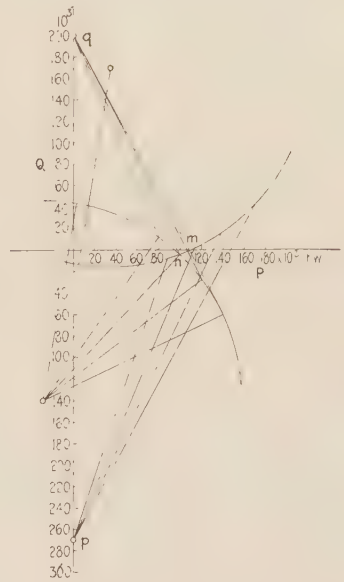

Fig. 12

trials the point n can be determined for which $\phi_1 + \phi_2 + \phi_3 = \phi$. This value of power indicates the maximum that can be transmitted at c.

The general method can best be illustrated by means of a solution of a particular case. The example chosen is that indicated on the eighth page of Miss Clarke's paper which involves the determination of the steady-state limit for a 270,000-kv-a. generator, transformers, a 250-mi. line and a 170,000- kv-a. synchronous motor. Complete details of line and machine characteristics are given on the sixth page of the paper. The voltage at the generator terminals will be maintained at an equivalent of 220 kv. and that at the receiving end at 200 kv. by hand regulation.

The combined constants for transformers and line are:

$$A_2 = 0.8431 + j\,0.0279$$
$$B_2 = 39.6 + j\,232.1$$
$$C_2 = (0.0104 + j\,1.248)\,10^{-3}$$
$$D_2 = 0.8428 + j\,0.0280$$

These constants enable one to construct the sending and receiving power circle diagrams in the ordinary way. These are indicated by the full lines in Fig. 11.

The center of the receiving circles for network 1 is located at $-\dfrac{\hat{A}_1}{\hat{B}_1}\,E_b^2$. Since this network contains only the generator reactance

$$\check{A}_1 = 1.0$$
$$\check{B}_1 = 0 + j\,X_1$$

and

$$\frac{\hat{A}_1}{\hat{B}_1} = \frac{1}{-j\,X_1}$$

$$-\frac{\hat{A}_1}{\hat{B}_1}\,E_b^2 = -j\,\frac{E_b^2}{X_1}$$

$$= -j\,\frac{220 \times 220{,}000}{179.2} = -j\,270{,}000 \text{ kv-a.}$$

Incidentally, this is equal to the sustained short circuit kv-a. at 220 kv. This point is indicated by the letter p on Fig. 3. The reference line coincides with the axis of reactive power.

The center of sending circles for network 3 is obtained in a similar manner.

$$\check{D}_3 = 1.0$$

$$\check{B}_3 = 0 + j\, X_3$$

$$\frac{\check{D}_3}{\check{B}_3} = \frac{1}{j\, X_3}$$

The center is located at

$$\frac{\check{D}_3}{\check{B}_3} E_s^2 = \frac{E_s^2}{-j\, X_3}$$

$$= j\, \frac{200 \times 200{,}000}{200} = j\, 200{,}000$$

This point is plotted at q, the reference line being the axis of reactive power.

Now give ϕ_2 an arbitrary value, say 34 deg., and determine

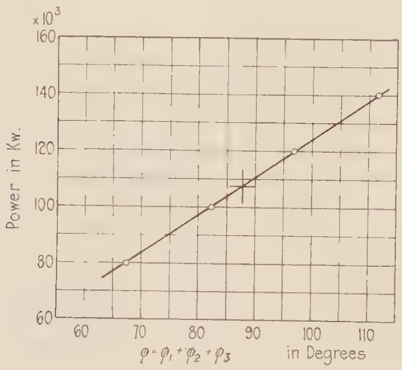

FIG. 13

m and n for this value. Draw $m\, p$ and $n\, q$ and measure ϕ_1 and ϕ_2.

$$\phi_1 = 22.3 \text{ deg.}$$

$$\phi_2 = 26.0 \text{ deg.}$$

$$\phi_1 + \phi_2 + \phi_3 = 82.3 \text{ deg.}$$

The total angle between internal voltages is then equal to 82.3 deg. for 100,000 kw. transmitted at receiving end. Choose a different value of ϕ_2 and repeat. By this means the curve shown in Fig. 4 can be obtained.

Substituting in the equation for B_0, this constant is found equal to

$$B_0 = 28.6 + j\, 506.7$$

$$\phi = \tan^{-1} \frac{506.7}{28.6}$$

$$= 518.7$$

$$= 86.7$$

From Fig. 4 the maximum power, which occurs for $\phi = 86.7$ deg., is equal to 106,500 kw. which value checks the result obtained by Miss Clarke.

C. A. Nickle: There seems to be a misunderstanding of what the authors intended to convey by their use of the terms "steady-state power limit" and "transient-load power limit." To make this matter clearer, let us consider three cases of load change which may be classified as transient changes.

First, let us consider the change involved in throwing on a load. Before the load is thrown on, the line will have a certain voltage and the synchronous machines will have their magnetic circuits excited to give this voltage. Under this adjustment, the line will carry a definite maximum load of the type to be thrown on. What the authors intended to convey was that it makes very little difference in the ability of the system to carry the load whether this load is thrown on gradually or rapidly or even instantaneously.

Second, consider dropping a section of the line. We do not intend to say that the steady-state power limit to be used is that of the line before the section is dropped. The steady-state power limit to be used is the limit of the line with the section out and our tests again indicate that we can drop a section of a line which is carrying power so as to leave the remaining section with a load equal to its steady-state value and that this may be done gradually or quickly.

Third, consider the case of short circuits. In the case of three-phase short circuits, of course, no power can be transmitted beyond *the short circuit; that is, the final steady-state power has been reduced to zero*, and the load at that point will be dropped unless the relays relieve the condition very quickly. In the case of single-phase short circuits, the line has been weakened in its ability to carry steady-state power but the amount will be a definite value. If we take this same line with the short circuit permanently on and calculate its steady-state power limit,—that is, for loads slowly applied,—this will give the same value as when the short circuit is suddenly applied, the magnetic adjustment of the synchronous machines remaining unchanged.

It is very important that we choose the proper steady-state power limit. The reason single-phase short circuits are severe is because they reduce the value of the steady-state power which the system can carry. When we were able to carry 31 per cent of the steady-state power of the line before short circuit it meant that the steady-state value to be used was the value with short circuit on the line. If we increase the steady-state power limit by means of special excitation systems, such as mercury arc and other schemes, we also increase the transient power limit to the same value. In every case where we have tried this on the miniature system, we have been able to create any condition suddenly that we could produce slowly and still maintain synchronous operation.

Edith Clarke: Mr. Evans and Mr. Wagner have stated in their discussions that the methods used in my paper to obtain the maximum power which can be transmitted over a given transmission system under steady state are applicable for constant field currents and when the voltage is regulated by hand, but do not apply when there is an automatic voltage regulator on the system. Mr. Spencer has asked how the constant generator reactance, which is to be used in the calculations for maximum power, is selected.

In order to answer satisfactorily, it will be necessary to define constant field or fixed excitation and hand regulation and to explain what is meant by *equivalent* synchronous impedance.

For simplicity, assume a synchronous generator and motor on the same bus with constant and equal fields on both machines; then increase the load until the machines fall out of step, plotting power delivered *vs.* terminal voltage. If this is done for a number of different field currents, it will be noted that there is one curve in which maximum or breakdown power occurs at normal terminal voltage. On the curves corresponding to lower field currents, maximum power occurs at voltages below normal, while on curves corresponding to higher field currents, maximum power occurs at voltages above normal. With given fixed excitations maximum power will not in general occur at normal voltage. When hand regulation is used and load is slowly added so that normal voltage is maintained, the maximum power limit is usually understood to mean the power corresponding to that fixed excitation for which breakdown power occurs at normal terminal voltage.

It has been found by tests that with regulators such as are used commercially today, it is not possible to transmit more than the maximum power limit as defined above by hand regulation. I agree with Mr. Evans that if regulators were fast enough to maintain terminal voltage, the machine impedance could be

neglected; or if fast enough to maintain constant flux, then leakage reactance could be used; but until something is done to increase their speed of operation, the maximum power limit with voltage regulators will be the limit obtained by hand regulation.

Equivalent synchronous impedance is a fictitious value used for convenience to obtain maximum power. The field current corresponding to it is a fictitious current and does not represent actual field current. The justification for using *equivalent* synchronous impedance is that by its use the calculations have been greatly simplified and the calculated maximum power has been found to give a satisfactory check upon test values.

For a given machine, the sustained impedance which replaces leakage reactance and armature reaction is not constant, except for a machine of zero saturation, but varies with terminal voltage, power factor and load. The *equivalent* synchronous impedance likewise is not constant for a given machine but depends upon terminal voltage, power factor and load. In steady-state stability problems a voltage regulator is assumed; therefore maximum power is obtained at normal terminal voltage. The power factor on the generator for long lines heavily loaded is not far from unity. The load on the generator may be estimated after one approximation. Therefore, terminal voltage is known and power factor and load can be estimated.

When the leakage reactance, the armature reaction, and the saturation curve of a generator are given, the following *equivalent* synchronous impedance has been found to give a good approximation for maximum power.

Equivalent synchronous impedance = (leakage reactance)

$$\text{plus}\left(\text{armature reaction} \times \frac{\text{slope of saturation curve}}{\text{slope of air gap line}}\right).$$

The leakage reactance will be given in per cent values. The armature reaction should be expressed in per cent of the air-gap ampere-turns corresponding to no-load normal voltage. The slope of the saturation curve should be obtained at a point corresponding to virtual voltage. Virtual voltage depends upon terminal voltage, power factor and load, and may be estimated, but in general the slope of the saturation curve at normal terminal voltage may be used.

With voltage regulators or with hand regulation, the maximum or breakdown power will occur at normal terminal voltage so that the same value of *equivalent* synchronous impedance will be used and the same value for maximum power will be obtained in either case. With fixed excitations, however, the conditions are different since the voltage at which maximum power occurs is not given. The procedure is not so direct as where normal voltage is maintained but *equivalent* synchronous impedance may be estimated and maximum power obtained after one or two approximations.

R. D. Evans and C. F. Wagner: Mr. Sels makes a plea for a definition of stability limits, so that we may all know what the other fellow is talking about. We might refer to the definition as given in our paper in which we say that the stability may be defined as the capacity of a power system to remain in equilibrium under steady-load conditions and its ability to regain a state of equilibrium after a disturbance has taken place. The first part of the definition is referred to as static stability and the second part as transient stability.

Mr. Sels believes that the static limit is of the utmost importance. He believes that in the future it will be possible so to improve insulation that insulator failures will be very rare. We hope that such will be the case, but we are living in the present, not the future. For that reason, we believe that transient stability is of more importance at the present time than static stability.

Mr. Sels also stated that we have the stability problem present in all metropolitan systems. In general, however, the stability calculations for metropolitan systems are much more difficult and complicated than for long-distance transmission systems. In the latter the line constitutes the greater part of the impedance between the two points considered, the impedance of the terminal equipment acting more in the nature of a correction factor. In addition, generators at each end of the transmission line can be grouped together and considered as units. In metropolitan districts the connecting impedances are much more complicated and in most cases it is not permissible to simplify the problem by grouping the generators into two groups. The effect of faults and changes in voltages is more problematic.

The curve presented by Mr. Powel showing the relation between transmitted load and the probability of outage is both interesting and important. It would seem desirable to obtain similar data on the operation of other existing systems. Such data might be analyzed in a number of ways, one of which would be the plotting of the number of outages for different loads. Such a curve would take into account the load cycle under which the system is operated, and also the variation in the probability of failure during different parts of the day. Ater a considerable amount of data were available, it would be possible to plot curves for each of the various types of disturbances, such as low-tension faults, three-phase faults, and flashovers to ground; and from a study of these curves to determine the amount of consideration which should be given to each type of disturbance in making additions to existing systems, or in laying out new projects. In order to compare data on different systems, it would be desirable to plot the outage curve in terms of the angle between supply and receiver ends. This function would form the basis of comparison of operation of different systems. The collection of such system-operating data can best be obtained by the use of such recording instruments as described in the paper by Mr. Wilkins and in the discussion by Mr. Legg.

In connection with Mr. Doherty's discussion, we agree with him that the static limit is a more definite quantity than the transient limit. The point which we wish to emphasize is that system stability under disturbances is the more important problem and that the transient stability limit is the more important limit. We agree that with fixed excitation in machines, the maximum limit is quite a definite quantity. However, this limit is not the same as the limit of a system operating with voltage regulators for the case of slowly increasing loads. Under this condition of operation, the true static limit will be in excess of the limit determined by fixed excitation. This arises because of the phenomenon which, in our paper, is termed "artificial stability." It is stated in the paper by Nickle and Lawton, and is endorsed by Mr. Doherty, that the only function of the regulator is to increase automatically the excitation as the load is applied, the actual limit being the same as that for hand control. Our paper presents results of analytical work on this problem which indicate that a condition of artificial stability in which the system is held together merely by the action of regulators, is possible. Since this paper was written, these results have been verified by experiments. The set-up consisted of a d-c. motor, a-c. generator, artificial line, an a-c. synchronous motor, and a d-c. generator loaded on resistors. With hand regulation, increasing the excitation to maintain constant terminal voltage as the load was slowly applied produced a limit of 65.1 kw., and with voltage regulators 79.6 kw., an increase of some 20 per cent. Mr. Doherty states that tests which he has carried out have not shown the existence of stable operation for loads beyond the static limit determined by hand control. He does not deny the possibility of such operation, but merely states that he has not found such a condition. It is possible that this disagreement may be ascribed to differences in the mechanical inertia and in the time constants of machines, particularly of exciters.

While we point out that this additional limit is available, we do not wish to imply that we advise working to this limit in ordinary operation. It should be recognized that this limit is available, and that advantage could be taken of it for emer-

gency operation. This matter of artificial stability, however, is largely one of academic interest. We do not wish to emphasize it too strongly. The real limit of practical importance which we have pointed out, and have tried to emphasize, is the transient limit. It is gratifying to find that the tests of Messrs. Nickle and Lawton on miniature systems bear out this contention.

Prof. Dwight has called attention to the difference in the method of plotting reactive kv-a. in power-circle diagrams. In the absence of an A. I. E. E. standard governing this practise, the various investigators have used the convention that seemed to them most logical and convenient. We heartily endorse Prof. Dwight's plea for A. I. E. E. standardization ruling on this point.

Mr. Barfoed brings up the matter of line insulation and circuit-breaker performance for 220-kv. systems, as affecting the general stability problem. In addition, Mr. Wilkins has called attention to the fact that 220-kv. circuit breakers may have a small time lag between the opening of the three poles. This difference in time in the test described by Mr. Wilkins was due to the failure to secure simultaneous mechanical opening of the three poles of the circuit-breaker. This is evidenced by the fact that the time required for opening the breaker was closely the same and independent of the load carried in the various tests. The oscillograph records also showed the time of arcing was approximately the same on the three poles, and could not be responsible for the period of about 0.2 seconds from the beginning of arcing on the first pole to the final interruption of the circuit. The 220-kv. circuit breakers can be adjusted to open the contacts on the several poles in about a cycle, as measured by the cycle counter. Furthermore, it may be pointed out that in the new breakers for 220-kv. service, further improvements have been made which secure more positive action, and facilitate adjustment in the field. Tests of a type similar to that described in the paper have been made subsequently, and in these it was found that the difference in time of operation at the three poles was less than two cycles.

Mr. Withington has called attention to the fact that the power limits at 25 cycles are considerably higher than at 60 cycles. This is a pertinent point in connection with the selection of the frequency to be used for railway electrification and general power purposes.

Mr. Roy Wilkins: It might be worthwhile to give the actual operating experience to reassure those who contemplate building such lines that they can be operated. One line has been in operation for twenty-two months and the other about nine months. There have been twenty-six total cases of trouble, of which two were mechanical, four were caused by birds (which was definitely known since the birds were killed), two by lightning, and five were located but the cause not known. The remainder have never been located. Four of these interruptions, of which two were mechanical and two caused by lightning, caused interruptions of one line of longer than three minutes. The balance were momentary line interruptions and the line went back without any change whatever. These lines are normally charged from the generating plant at reduced frequency, usually thirty-five cycles, in which they build up with the field circuit open, to the normal voltage and little above normal current. The condenser is then put on at the receiving end and they are brought up to full frequency and paralleled at the receiving end. Thereafter the load is pulled up and they are paralleled at the sending end. Customarily, this is carried out without any dispatching whatever, and the whole procedure has been carried out in approximately one minute. In times of great stress, for instance, if one line goes out over the peak when the load is high, we charge the full 202 miles back to the system and parallel at the power house. This gives a voltage rise at the substation end of 10 per cent and is not customarily carried out.

The two lines, by the ordinary method of analysis, will carry about 198,000 kw. each. We plan never to run over 120,000 kw. on them. At such time that the load increases above this point, segregating points will be added in the line. When development requires, there will be four complete lines.

The question has been brought up about the oscillographic wattmeter and meters. This oscillographic wattmeter is more or less of a novelty. It is felt that it is reasonably accurate. It requires so little power that the ordinary bushing-type transformer will supply it without serious error in ratio and it will record disturbances lasting as short a time as about $^1/_{20}$ sec.

DIELECTRIC ABSORPTION AND THEORIES OF DIELECTRIC BEHAVIOR[1]

(Whitehead)

and

THEORY OF ABSORPTION IN SOLID DIELECTRICS[2]

(Karapetoff)

New York, N. Y., February 8, 1926

A. E. Kennelly: In Faraday's time, the properties of substances under magnetic stress or magnetization, and the properties of dielectric materials under dielectric stress or electric induction, were studied and were regarded as of great interest by him and by his followers.

It seems remarkable that, using the relatively feeble magnetic stresses and magnetic fluxes of ordinary dynamoelectric machinery according to Ewing's theory, it is not necessary to go deeper perhaps than the molecules of the iron or steel in order to account for the main features of magnetic induction. No doubt when we come to consider much more powerful magnetic stresses such as in the Zeeman effect it may be necessary to go deeper than merely into the molecule, or into groups of molecules. On the other hand, however, in order to account for the behavior of dielectric material under electric stresses, it seems that even with the relatively feeble stresses of electric signalling, a consideration of groups of molecules or even of molecules themselves is inadequate, and it seems necessary to descend to the subatomic state to explain the phenomena.

Strange to say, in the early history of electrical engineering, going back to the time when the only electrical engineers were the telegraph engineers, the study of dielectric absorption was found necessary for practical purposes, in order to specify the insulation resistance of a given length of any kind of solid insulated conductor. It was necessary as our textbooks show, as far back as the 1850s, to take some account of dielectric absorption, and it was known that the apparent insulation resistance at the beginning of the first quarter-minute was different from what would be obtained at the first half-minute or at the first minute. It became necessary, I think, in the 1860's, to define the measured insulation as that obtainable at a certain definite interval of time, let us say one minute or three minutes after the application of the continuous dielectric stress.

W. A. Del Mar: I have run into the same difficulty that Professor Whitehead mentioned; namely, that the physicists who are working on the theory of electrons and the ultimate nature of matter have not reached a stage of progress in their work where they can help us very materially in our theories of absorption in electric strength, and I don't believe that very great progress will be made until the physicists who are dealing in those ultimate matters make some further steps forward.

A few years ago I would have thought that the experimental physicists and those who are dealing with such matters as electric strength and absorption were the ones who would have to take the principal steps in order to reach a rational theory of the behavior of dielectric, but I have now come to the view that the pure scientists are the ones upon whom we are waiting.

We must be careful, in studying such a subject as dielectric

1. A. I. E. E. Journal, June 1926, p. 515.
2. A. I. E. E. Journal, March, 1926, p. 236.

loss and power factor, not to put a word in place of a phenomenon and take refuge behind the word. There is a little danger that we may do that with the word "absorption". It is taken to cover a multitude of sins, and when one reads through Professor Whitehead's admirable summary, one has to stop occasionally and think: What is the meaning of this "absorption?" Is it not just a word which is being used in a general way to cover a great variety of phenomena?

One might perhaps get the impression, by reading Professor Whitehead's summary, that there are several theories which might be chosen from, to explain the phenomenon, whereas more likely all of these theories will be required in some measure to explain it in full.

R. E. Marbury: Dr. Whitehead has given us a very complete review and valuable bibliography of what has been done on dielectric absorption and related phenomena.

Our experience has indicated that Maxwell's theory can explain dielectric absorption and a-c. losses of the low frequency type. Maxwell's theory assumes that the s. i. c. and resistivity of the dielectric remain fixed. This is generally the case in solids, but with semi-liquid dielectrics, such as oil-impregnated paper, there is evidence of changes in either s. i. c., resistivity, or both, with voltage, or temperature. This may be illustrated by plotting the residual voltage under a fixed set of conditions, against various applied voltages. If the law of superposition holds and if the resistivity and s. i. c. remained fixed throughout, a straight line relation would be found. This is not the case, as we find that the residual does not increase proportional to voltage. In some specimens the applied voltage may be doubled with little effect on the residual. The conditions may be changed so as to modify this relation. For example, if the duration of charge is made very small, such as 0.0015 sec., the resulting curve may be a straight line and appear to follow the law of superposition. This, among other things, leads us to believe that this departure from the law of superposition is caused by a movement of moisture, and when the duration of charge is made too quick for the moisture, the dielectric acts like a solid, as is to be expected.

A dielectric which shows this non-proportional residual possesses other interesting characteristics. For example, the losses will decrease with increased voltage. Such a dielectric will show a marked decrease in losses with time after the application of voltage. The latter effect may be seen by measuring the losses at five-sec. intervals, starting five sec. after the voltage is applied.

It is now possible to predict quite definitely certain characteristics of a condenser from absorption tests of the proper type. These characteristics are:

1. Whether the losses will decrease or remain constant with voltage.
2. How the capacity will vary with frequency.
3. Completeness of drying process.
4. Magnitude of loss variation with temperature.
5. Whether the condenser will give good performance on alternating current.
6. Whether the condenser has characteristics desirable for d-c. operation.

We can predict less accurately the actual losses, and can calculate a curve which will have a shape closely following the real curve which will be found if losses are plotted against voltage.

It appears that a complete interpretation of absorption curves will make possible a closer control of dielectric characteristics than has heretofore been possible.

R. W. Atkinson: I wish to remark that great increase in our knowledge of dielectric phenomena is certain to be made in the next few years on account of the interest and attention given these problems by the leading physicists in the faculties of the colleges and universities of this country. The present and other recent contributions are an important part of the recent advance, especially as leading toward a clearer understanding of dielectric phenomena.

When Mr. Fisher, for our company, first began measuring dielectric losses, before I was associated with him and also during the early part of my work, we found it useful to measure both quantities, dielectric absorption and dielectric loss, and a very close relation between them was observed, and for a long time both measurements were faithfully made on all materials.

Later, the large increase in the number of dielectric loss measurements necessitated that attention should be concentrated on the loss end of the problem. But I believe it is important to have further investigation of the absorption side, and have no doubt it will lead to valuable knowledge of the subject.

I believe that the greater part of the losses in paper cable dielectrics at high temperature can be quite largely accounted for by specific numerical application of Maxwell's method.

E. S. Lee: If you will look into the bibliography which Dr. Whitehead has prepared, you will find some three hundred and fifty items, and yet we have the work of Tank—one man—given to us as "apparently the only effort so far made for a direct check between measured loss and loss computed from measured absorption."

I think that is a condition about which we ought to think and I think that it is largely because of that condition that Professor Karapetoff worked out a formula which we could use in this regard. In other words, if, for any insulation we shall determine the curve of current against time and determine it well,—that is, allow the insulation to retain its initial condition between each measurement and obtain the curve with which we are familiar and then obtain the constants M and N, which you will find in Professor Karapetoff's paper, from that curve,—then the dielectric power loss of the insulation may be calculated from the equations given. This value may then be compared with measured values, and we shall be able to determine whether or not the equations which Professor Karapetoff has derived are applicable to the work which we have at hand.

We have tried to do this, somewhat, and have found, thus far, that out of 13 articles in the literature, only one had data which we could substitute in these equations.

So I make a plea to those of us who are interested enough to obtain data, that we shall obtain it in such a manner that we may make proper substitutions into the formula which Professor Karapetoff has derived in order to determine whether or not it applies. When you consider all of the work that Dr. Whitehead and his Committee have done, and when you find the meager amount of data that is available for substitution directly into such formulas as we have, it seems as though we had overlooked something in connection with the work, which should be rectified in the future.

D. W. Roper: Dr. Kennelly, I believe, stated that our knowledge of this subject was far from complete.

And Mr. Lee apparently has somewhat the same idea, because, after a careful study of the paper, he picks out one sentence which sums up the knowledge that he was able to use on the subject.

Now, if there is all that difficulty in getting some real knowledge about the very simplest forms of insulation, how much more difficult and how much more remote is the chance of our getting some fundamental knowledge regarding such a very complex insulation as impregnated paper, such as is used in our lead-covered cables. Dr. Whitehead touches upon that point a little in his final paragraph.

I have been endeavoring, with a very great effort, to find some method of measuring the quality of the insulation without destroying the insulation, and apparently there is no such method. We don't know enough about insulation to measure the quality, without destroying it, and so what we do in practise is to measure the quality of some samples of insulation and then include in our cable or our machinery some insulation which is similar

to the samples we have tested; and we hope that the insulation which we use will be just as good as the samples. Until we can get more fundamental knowledge of the properties of the insulation, we shall not be able to replace that hope with knowledge.

J. Slepian: Equation No. (10) in Dr. Whitehead's paper and No. (21) in Professor Karapetoff's, written with a little different notation

$$D = K_o E + \int_0^t E(u)\, \phi(t-u)\, d u \qquad (1)$$

is a very interesting one and gives a complete account of the electrical behavior of a dielectric in those cases in which it applies. Professor Karapetoff has called the function ϕ a relaxation function. Another viewpoint is to call the function a memory function, as this function indicates how much the dielectric remembers of the voltage which has been impressed upon it in the past. As will be seen in Fig. 1, if $E(u)$ represents the voltage gradient which has been applied to the dielectric from the time $u=0$, then at the time $u=t$ the displacement of the dielectric according to the above equation depends not only upon the value of E at the time $u=t$ but on all the preceding values. However, the preceding values are not taken with equal weight but are multiplied by a factor which diminishes as the time recedes further into the past. The function $\phi(t-u)$ represents this weighing factor. In other words, it shows how the dielectric has a diminishing recollection of past voltages.

The equation (1) follows directly from the principle of superposition, as both Professor Karapetoff and Professor Whitehead

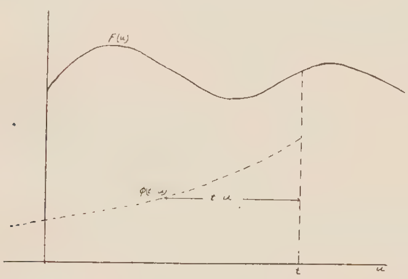

FIG. 1

bring out. It is also true that solutions of linear differential equations with constant coefficients can always be expressed in the form of equation (1). The simplest memory function is probably that which corresponds to a first order linear differential equation and that is a simple exponential. The memory functions of higher order differential equations are made up of sums of exponential functions. If a number of electrical systems, each satisfying a first order linear differential equation and therefore having a simple exponential memory function, are coupled together in any way, the resulting system is characterized by a linear differential equation of high order, with a more complicated memory function. Likewise a given system with a complex memory function is equivalent in its action to a large number of simple systems coupled together.

The resolution of the complicated system into simple systems is quite indeterminate and can be effected in a variety of ways. Referring specifically to the problem of the dielectric, it has been attempted to resolve the dielectric with complex memory function into an aggregate of dielectrics with simple memory functions, but such resolutions are indeterminate and usually of little value unless properties other than checking ordinary electrical measurements are considered. Maxwell, Wagner, and others suppose the dielectric made up of an assemblage of materials, each having a simple dielectric constant and ohmic resistivity. Karapetoff makes the dielectric consist of an aggregate of small pieces of dielectric, each piece having a simple memory function, without explaining how it comes to have that property. Von Schweidler assumes various kinds of molecules each with its own memory function combining to give a more complex memory function to the dielectric.

All of these theories lead to the same result,—namely, the equation (1)—and say no more than that the principle of superposition applies to the dielectric. Maxwell & Wagner's theories will have value only in those cases in which portions of the dielectric can actually be found which have simple dielectric constant and ohmic conductivity. Karapetoff's theory likewise will have value only if he can actually determine by means independent of the ordinary electrical measurements, the existence of portions of dielectric having simple memory functions. Von Schweidler too must show independent evidence of the existence of his various kinds of molecules. All these theories are sufficient to account for the principle of superposition. None of them is necessary. It seems to be a choice of being satisfied with the idea of the homogeneous substance having complex dielectric properties or a complex assemblage of materials having simple dielectric properties. Unless, however, there is physical evidence of some kind for the existence of the complex assemblage of simple substances, I do not believe that anything is gained over the assumption of the homogeneous substance with complex characteristics. As far as agreeing with electrical measurements, all these theories are on a par, provided they accurately represent the memory function of the dielectric.

That these theories without other physical evidence do not add to our knowledge of the dielectric seems to be intimated by Professor Whitehead when on page 11 he says of Von Schweidler's theory "The analysis has the character of a mathematical fiction," and again further along on the same page, in speaking of the check which Grover made upon the Pellat theory, "It appears certain that an equally good agreement would have been obtained from Wagner's equations; in fact it is safe to say the same of any theory providing for the medium a sufficient number of terms, all obeying a continually decreasing function $\phi(t)$ of relatively simple form but with different values of the constant terms."

While it is true that a heterogeneous assemblage of simple dielectrics will show absorption and satisfy the principal superposition, it does not follow that a material showing absorption is necessarily heterogeneous, and to my mind the physical evidence on that point is far from conclusive. Very pure substances show little absorption, but, at the same time, they usually show a tremendously high resistance. When two pure substances are mixed they frequently show absorption, but such mixtures are hardly to be described as heterogeneous and the absorption which arises frequently is not consistent with the numerical values of the dielectric constant and resistivity of the pure materials themselves. For example, a mixture of pure water and pure sulphuric acid shows a great conductivity which cannot be accounted for on the theory that it is a heterogeneous assemblage of the pure substances, each of which has a tremendously high resistance.

How universal is the principle of superposition for dielectrics? The existence of the irreversible current which Dr. Whitehead points out shows at once that it does not always apply. Last year Mr. Marbury, in his paper on oil condensers, showed phenomena which contradicted the principle of superposition. The departure from the law of superposition may take place in various ways. First the memory function may change with time of application of voltage as, for example, when water in the pores of a material is displaced gradually by the electric field. The memory function may change with amplitude of voltage as it undoubtedly does near the dielectric breakdown point of the material, or finally the properties of the material may not be characterizable by a memory or relaxation function at all.

The paragraphs of Professor Whitehead on electric hysteresis, I think, are exceedingly good and to the point. The phenomena of dielectric absorption and magnetic hysteresis are too unlike in character to be confused by a similar name. In the language

of my preceding discussion, whereas a dielectric has memory of past electric fields which diminishes with lapse of time, a piece of iron has an unchanging memory of the fields which have acted upon it. You may put a piece of iron through magnetic cycles today and tomorrow the iron will be ready to go on from where it left off, no effect of the magnetic fields of the previous day being lost.

The work of Debye and Schrodinger, I believe, deserves more than the casual mention which Professor Whitehead gives. Their polarized molecules have an actual physical reality, since, in their work on dielectric constants of gases, they are able to explain the dielectric properties by assuming that all the molecules of the gas are polarized with moments of the order of magnitude consistent with other phenomena and are able to predict correctly the effect of temperature by calculations from the kinetic theory of gases; thus Debye and Schrodinger give a complete theory of the dielectric properties of an un-ionized gas, the only case in which such complete theory has been given.

I wish to take issue with Professor Whitehead with respect to what he calls the fundamental equations of electromagnetism. In his classification on page 7 he implies that some of the theories given involve deviations from the fundamental laws. I believe the common usage is to regard the following equations as given by Maxwell fundamental:

$$\text{Curl } E = - \frac{d^B}{d\,t} \tag{1}$$

$$\text{Curl } H = 4\,\pi \frac{d\,D}{d\,t} + 4\;C\,\pi \tag{2}$$

$$\text{Div. } B = O \tag{3}$$

$$\text{Div. } D = -\,4\,\pi\,\zeta \tag{4}$$

These equations correspond respectively, the first to Faraday's law of induction, the second to the manner in which conduction and displacement currents give rise to magnetic fields. The third equation states the fact that free magnetic charge does not exist, and the fourth, that lines of electric flux terminate in electric charge. These four equations are not sufficient to determine the quantities E, H, B and D, but further relations must be found connecting B and H and D and E, depending upon the properties of the material considered. In the simplest theories, it is customary to take $B = \omega\, H$ and $D = \epsilon\, E$. These last equations are the ones which are not adopted by some of the theories which Professor Whitehead mentions. However, they are not fundamental in electromagnetism; they are only a very special case in electromagnetism.

C. A. Adams: As I was originally responsible for the organization of the Insulation Committee, of which Dr. Whitehead's excellent paper is a one-man report, I am naturally interested in its progress.

But the attack which I had in mind was a very much more vigorous one that is now being conducted largely by voluntary services.

A more thorough understanding of dielectric phenomena in solid and semi-solid dielectrics constitutes the most important problem in the whole field of electrical engineering at this time. But unfortunately it is a terrifically complicated and difficult problem from the standpoint of modern theory. It has been almost completely ignored or shirked by our American physicists, and the very suggestive and interesting first steps taken by two or three foreign physicists are buried in the proceedings of the more highly scientific organizations.

This most important problem is not going to be solved by engineers. We need a comprehensive fundamental research involving the cooperation of the best physicists and chemists that the world affords, and backed financially by the great corporations who either manufacture or use insulating material. The cost to any individual corporation would be small, if they all took part, particularly if the cooperation were extended to other countries, as it should be in a problem of such fundamental scientific and commercial importance.

Much research work in this field is now being conducted in this country, but mostly by engineers, who, owing to lack of thorough knowledge of modern theory, are only skimming the surface. Moreover, there is no thorough cooperation, and much duplication of effort.

If the A. I. E. E. wishes to stand for cooperation and progress, here is certainly a supreme opportunity.

S. L. Gokhale: I have nothing to contribute directly to the topic under discussion; my purpose is merely to supplement the very suggestive remarks of Dr. Kennelly by an interesting experiment of ours in the General Engineering Laboratory.

Dr. Kennelly has suggested that the dielectric phenomena are perhaps sub-atomic in their nature; he also referred to the magnetic phenomena as being analogous to the dielectric phenomena, so that any insight into the one phenomenon might help to give us a better understanding of the other. The experiment I am going to describe refers to magnetics, and I am describ-

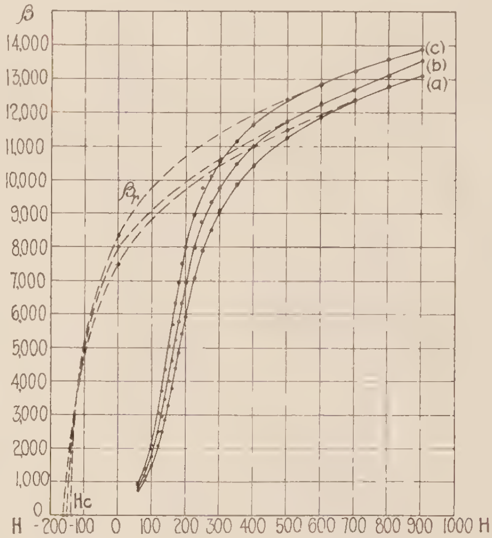

Fig. 2—Cobalt Magnet Steel (Sample No. 16-1) Change of Magnetic Characteristics Apparently Due to Strong Magnetizing Force

ing it in the hope that it may prove of use to those who are trying to study corresponding phenomena in dielectrics.

The sample under test was a toroid ring sample of cobalt magnet steel, wound for a magnetizing force of about $H = 1000\,g$. The resulting curves are shown in Table I. The curve (a) is the result of the first test; the point for $H = 900$ gave at first $\beta = 13{,}000$, but the reading could not be repeated on second and subsequent tests, and on going back it was found that other points could not be duplicated also. The whole test was therefore repeated, and gave the curve (b). At $H = 900$, the curve developed the same anomaly as before. The whole test was therefore repeated once more, which gave the curve (c). A fourth test gave a further shift of about 50 gausses with a corresponding increase of deflection of half a millimeter. The sample seems to have reached a steady state now. The hysteresis curve (dotted) is conjectural, but the cardinal points $\beta\,r$ and H_c are observation points. It seems that during the test the sample was softening, probably under the influence of the strong magnetizing force. It was probably not a heat effect, as the precaution against heating had been tried out in some previous tests, and was found to be quite satisfactory; no thermic measurements were made in this particular case.

In trying to interpret the phenomenon, my first guess was that there was some change in the structure of the molecular

COBALT MAGNET STEEL

Ring-Form Sample No. P-16-1

Test (a)

H	β	βr	$H c$
60	750		
80	1050		
100	1500		
120	2080		
130	2450		
140	2850		
150	3300		
160	3800		
170	4400		
180	4850		
190	5350		
200	5950		
225	7100		
250	7900		
275	8520		
300	9100		
350	9880		
400	10450		
500	11250	7250	
600	11850	7350	
700	12400	7400	162
800	12800	7500	162
900	13100	7500	(Reading not duplicated
1000		No Test	on repeating)

Test (b)

60	800		
80	1200		
100	1750		
120	2500		
130	2960		
140	3480		
150	4020		
160	4600		
170	5250		
180	5800		
190	6350		
200	6950		
225	8020		
250	8780		
275	9350		
300	9780		
350	10480		
400	11000		
500	11750	7750	
600	12250	7750	
700	12700	8000	149
800	13100	8000	149
900	13550	8150	(Reading changed after
1000	No test		first reading)

Test (c)

60	920		
80	1400		
100	2100		
120	3050		
130	3700		
140	4350		
150	5050		
160	5700		
170	6350		
180	6950		
190	7500		
200	8000		
225	8950		
250	9750		
275	10100		
300	10550		
350	11150		
400	11650		
500	12400	8240	140.0
600	12850	8350	141.0
700	13250	8350	141.4
800	13600	8350	141.8
900	13900	8350	142.0
1000	14100	8350	142.0

systems which are supposed to be oriented during magnetization. This explanation implies a modification of Weber's theory, which refers to orientation of the molecules. On trying to discuss the question with my colleagues in the Research Laboratory, I was informed that in view of the recent researches about the structure of the crystals, as revealed by the X-Ray spectroscope, there is no intermediate step between an atom of iron and a complete crystal. The phenomenon of magnetism should therefore be regarded as an atomic or sub-atomic phenomenon, which leaves no room for Weber's theory of molecular orientation, and even less room for my theory of molecule-system orientation.

I do not claim to have understood the phenomenon; I am not even convinced that it is sub-atomic. I am mentioning it here in the hope that it might help in some way towards a better understanding of the process of magnetic polarization in the first place, and of dielectric polarization by analogy.

J. B. Whitehead: All writers on the theory of dielectric absorption have discussed the form of the curves of current of residual charge and discharge. A number of these are set forth in my present paper. All such workers have recognized that a single term of any of the forms mentioned will rarely represent the experimental curve. Hopkinson found for his samples that two terms were not enough, and Maxwell gave general expressions for n terms as required in a mixture of $n + 1$ materials. A number of observers have found that for some simple substances one term is closely sufficient.

Professor Karapetoff's paper is based on the assumption that a great many, perhaps an infinite number, of such terms are necessary. The Germans, Wagner and Von Schweidler, have also made this assumption and have attempted analytical developments which should in effect permit us to assign definite constants to particular materials which would fit the relative importance of this large number of terms and so define the behavior of the material. Professor Karapetoff has gone somewhat further, first in selecting a function fixing the distribution of the series of terms which is somewhat easier to handle, second in allowing us to follow more intimately his ingenious mathematical manipulation, and particularly in evaluating the changes which may be looked for under alternating voltage, in the values of conductivity and permittivity as affected by his "generalized absorption."

But while we may admire the persistence and skill manifested in these developments, I question seriously whether they constitute the necessary path by which we will ultimately reach a position in which we can control and predict the performance of dielectrics for the following reasons:

It has never been shown that $\phi\ (t)$ is uniform or the same for any given material. Why discuss $F\ (\alpha)$ if it may have widely different forms for the same material prepared in different places? The absorption of any material may be continually reduced by greater and greater care in purification. Hopkinson showed that while two terms were not sufficient to account for his curves, not many more would be required. Steinmetz showed that even in so highly absorbent a dielectric as cable insulation, three terms were sufficient to very closely account for the observed curve. There are many instances where one term appears sufficient. F. Tank has studied $\phi\ (t)$ for very small values of t, has found it of simple form, *i. e.*, one term, and that the use of a single term in developing the expression for loss under alternating voltage gives values in accord with experiment.

Professor Karapetoff states that the time for a rational theory of dielectric absorption has not arrived. One must ascribe this statement to momentary forgetfulness, induced by deep interest in the theory of Pellat, and his elaborate development thereof. I am sure that he will agree with me that Maxwell's theory of dielectric absorption, relying as it does only on fundamental electromagnetic theory, and in no wise invoking the structure of the atom, is in every respect a rational theory. Maxwell, as everyone knows, explains dielectric absorption entirely in terms of the specific conductivities and specific inductive capacities of

different substances when mixed together. It accounts qualitatively at least for most of the important phenomena to be observed in the dielectrics of practise, and does this quite as satisfactorily as any other theory. If it is not subject to exact experimental corroboration, it has certainly never been shown that this is not due to the impossibility of obtaining strictly pure and simple materials or mixtures. Maxwell himself recognized the probability of this difficulty and extended his expressions so as to embrace any number of different materials. Followers of his theory have always assumed that the several terms often needed to account for the shape of the curves of charge and discharge, are due to the presence of other substances or impurities throughout the mass of the principal dielectric. Wagner is a follower of Maxwell, and in his development of the distribution function he has attempted to picture the type and method of mixture of the conducting impurities in the mass of the dielectric. If this view is correct, and there seems to be no satisfactory contradiction of it, it would appear that the evaluation of distribution functions such as assumed by Von Schweidler and Wagner, and now by Professor Karapetoff, resolves itself into an effort to define the particular ways in which impurities may occur in a fundamental material. Obviously there is no reason to suppose that on this basis the distribution function can ever be the same in any two cases, even for the same fundamental material.

These questions have long excited the discussion of those interested in the theory of dielectric theory and behavior. The following are a few experimental problems the solution of which would go far toward solution of some of the open questions:

To fix the definite curves of particular substances, and the accuracy with which they can be reproduced.

To determine the importance of their departures from simple curves.

To study the control of these curves.

To study their behavior in combination in different substances.

To study the relation between absorption and loss for some of the simpler cases.

In my opinion careful work in these directions will be found to greatly simplify the present confusion as to the nature and behavior of dielectric absorption, and further will result in enormous simplification of the problem of engineering design and insulating mediums.

H. L. Curtis (by letter): Dr. Whitehead has reviewed a large amount of literature and has made an excellent summary of our present knowledge of the anomalous behavior of dielectrics. It is a fair and impartial discussion of all the theories that have been proposed to explain this most baffling phenomenon. It should serve as a starting point in the extension of our knowledge of dielectrics.

I agree with the author that, from a theoretical standpoint, the most satisfactory theory of dielectric absorption is that of Maxwell's stratified dielectric. However, I do not agree that there is any chance that it can explain all the observed facts. One illustration will suffice. The application to alternating current phenomena of Maxwell's theory or any of the modifications proposed by Rowland, Wagner, and others, invariably leads to an equation for the phase difference which is equivalent to equation (**31**). For high frequencies, this equation takes the approximate form

$$\tan \delta = \frac{k}{\omega T}$$

so that for such frequencies the phase difference is inversely proportional to the frequency. Now there are abundant data to show that this is not the case in many dielectrics. Hence in such dielectrics it appears impossible to explain the phenomena on the basis of this theory.

However, there are other dielectrics where the observed phenomena are largely explainable by Maxwell's theory. Moreover from the fundamental assumptions of this theory it must play some part, however small, in most absorption phenomena, since homogeneous dielectrics are extremely rare. The conclusion must therefore be drawn that the final explanation of dielectric absorption will include at least two theories of which Maxwell's stratified dielectric will be one.

Professor Karapetoff has given a very clear derivation of the integral equation (Eq. No. **21**) which results when the principle of superposition is applied to an absorbing dielectric in an alternating electric field. Wagner's relaxation function (Eq. **25**) is then inserted in this integral equation and the solution carried to a point where both the change of capacitance with frequency and the power factor are expressed in terms of integrals which involve both the relaxation function and the frequency. An empirical expression (Eq. **56**) for the relaxation function is then assumed and the integrals evaluated. The results (Eqs. **103** and **104**) are given in terms of ascending powers of the frequency. There is, however, no discussion of the convergence of these series. It is evident that, for high frequencies, they either diverge or become impracticable as methods of representing the function.

The value of the paper would have been greatly increased had it contained some numerical examples. At best the results as given are applicable only to low frequencies. Whether this includes frequencies that are of any practical or theoretical value can not be judged from the equations as given. Until the paper is completed by the application of the equations to typical sets of data, one should withhold judgment as to the value of the results obtained.

J. Katzman: Professor Whitehead's paper reviewing and bringing together the many theories of dielectric absorption and indicating the behavior of dielectrics under various conditions as found by former experimenters is certainly of inestimable value to all those engaged in this work. However, the divergence of views, theories, and results obtained makes it impossible, as yet, to predict effects from given causes. Qualitatively predictions can more readily be made, provided the knowledge of accumulated facts is had. Effect of temperature may be prophesied if it is known and remembered that according to Hopkinson and others, absorption current increases with temperature, and that according to Wagner, rate of absorption and decay is increased with temperature and the total absorbed charge remains unaltered. From Lahousse's equations it may be surmised that a loss in a dielectric will vary as the square of the voltage. Similarly, effects of frequency on loss per cycle, on loss per minute, and on capacity, and the effect of voltage

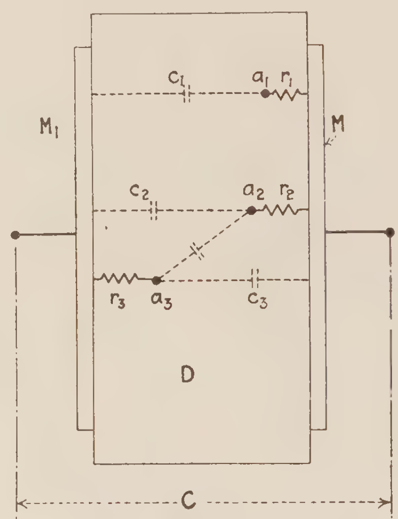

Fig. 3

on absorbed charge, etc., may be foretold if results of former experiments are remembered, or resorted to.

To be able to say, even approximately, what may be expected when a dielectric is made to undergo a change, is often of great value, and this may be deduced from a consideration of the properties of conductors and specific inductive capacity only. Assume the dielectric to have conducting particles embedded in it and the dielectric itself to have conductivity. Fig. 3 is a diagram of a condenser having a dielectric D, the metallic plates M_1, M_2 on the opposite faces of the dielectric, and some of the conducting particles a_1, a_2, a_3; r_1, r_2, r_3 are the resistance of the dielectric between respective plates and particles as shown. Each of the particles will form a sub-condenser with one of the plates or with each other as indicated. By forming a mental picture of such a condenser, all of the facts mentioned before concerning dielectrics can be reasoned out. Thus when the applied e. m. f. is altered, the charging current of each of these sub-condensers is proportionally altered and therefore $I_3^2\, r_1$, $I_1^2\, r_1$, etc., varies as the square of the voltage. The summation of these losses being assumed to produce the absorption loss, it is seen that absorption loss will vary as the square of the applied e. m. f.

With but very few exceptions when temperature is increased

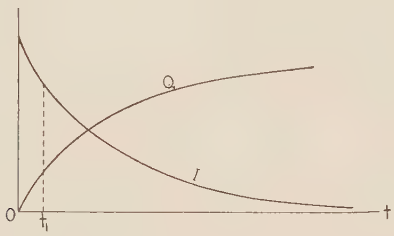

FIG. 4—CURVES OF VARIATION OF CHARGE AND CHARGING CURRENT WITH TIME

the resistivity of solid insulators reduces.[1] Hence resistances r_1, r_2, etc. reduce. The effect is therefore to reduce the time constants $c_1\, r_1$, $c_2\, r_2$, etc. of the sub-condensers, thus increasing the rate of absorption and decay, but does not alter the total absorbed charge, in accordance with Wagner's conclusions. The absorption current having increased, $I_1^2\, r_1$, etc. increases even though r_1 does decrease. The result to be expected then is an increase in power loss due to absorption.

When the frequency is increased the time available for charging the sub-condenser is decreased, and as can be seen from Fig. 4, if this time is t_1, the condensers will be only partially charged, with the result that absorption loss per cycle is decreased since the loss per cycle is $\int_0^{t_1} I^2\, r\, dt$. From the shape of curve I, it is obvious that the greatest loss occurs only at the beginning and therefore the reduction in loss is less in proportion as the frequency is increased. It follows then that the loss per second is increased by an increase of frequency. It is readily conceivable that the sub-condensers increase the capacity C by increasing the ratio Q/E, where Q is the total charge and E the applied e. m. f. At very high frequencies, however, the charge on the sub-condensers becomes practically zero, as can be seen from the curve Fig. 2, and hence the capacity of the condenser becomes equal to the geometric capacity. In other words the capacity of the condenser approaches the geometric capacity as the frequency is increased.

By similar reasoning, and these involving only elementary principles, other predictions may be deduced.

A further development of this idea is under preparation.

1. Dietric in Phys. Zs. 11, p. 187, 1910 shows that $R_t = R_0\, e^{\frac{-qt}{273(273+t)}}$ q being a constant depending on the material and t the temperature.

E. R. Le Ghait: Professor Karapetoff's mathematical analysis will certainly be of great interest to all those occupied with the behavior of dielectrics. He does not make any assumption on the physical nature of the phenomena. The work we have done with fibrous insulating materials has led us to the opinion that Maxwell's ideas are, in that case, quite capable of explaining the observed phenomena, provided however, one takes into consideration the complicated structure of the dielectric. We believe that the absorption as well as the dielectric losses at commercial frequencies are due for the greater part to the presence of very small quantities of moisture imprisoned in the capillary tubes of the fibers. If we then consider the dielectric as composed of a very great number of very thin paths crossing from one electrode to the other, and apply Professor Karapetoff's analysis, his function $F(\alpha)$ will be the law of distribution of the moisture among those paths. If the curve $F(\alpha)$ has a very pronounced peak it will indicate that all the paths have pretty much the same amount of moisture. If on the contrary $F(\alpha)$ is a comparatively flat curve it will indicate that some paths contain much more moisture than others.

If then the moisture is the cause of the dielectric loss the knowledge of the function $F(\alpha)$ will give us an indication of whether the loss is uniformly distributed all over the dielectric or whether it is for the greater part concentrated in some of the paths, these paths constituting possibly weak spots on account of the deterioration of the insulation due to an exaggerated loss in a given point.

Dr. Whitehead, in his comments of Maxwell's theory, calls attention to the fact that pronounced absorption is observed in substances that can have in them only small amounts of impurities. This is probably due to the peculiar shape of the lines of force in a dielectric containing materials of different specific inductive capacities.

Our own experience agrees with Dr. Whitehead's opinion that dielectric losses are closely related to absorption. In fact, in the case of unimpregnated paper, starting from residual voltage curves obtained with a dielectric previously left charged at 100 volts d-c. for a certain time and then left short circuited for a very short time, we are able to compute 60-cycle losses with less than five per cent error.

In the case of oil-impregnated paper, greater difficulties are encountered, as in that case the law of superposition does not hold true (this being probably due to movements in the oil under the influence of the electric field, of moisture and other components of high specific inductive capacity). In correlation with this, the power factor at a given frequency varies widely with the value of the applied voltage. It may, however, prove to be possible in the future to make a low voltage d-c. absorption test enabling one to predict with sufficient accuracy the a-c. losses at a voltage many times higher, and perhaps even to predict the curve of variation of power factor with applied voltage.

Discussion at Cleveland

PAPERS ON PAPER-MACHINE DRIVE

(STAEGE[1], ROGERS[2] AND NORRIS[3])

CLEVELAND, OHIO, MARCH 18, 1926

T. D. Montgomery: Mr. Staege says that a speed adjustment of from 0.1 to one per cent is required. Does this mean that some classes of paper require 0.1 per cent while others require one per cent, or that regulation anywhere between 0.1 per cent and one per cent meets all conditions of paper making?

Reference is made to differentials, either electrical or mechanical, and Mr. Staege refers to the accumulative lag in drive and master shaft and field clutch. Would there not be the

1. A. I. E. E. JOURNAL, March, 1926, p. 272.
2. A. I. E. E. JOURNAL, April, 1926, p. 323.
3. A. I. E. E. JOURNAL, May, 1926, p. 432.

equivalent lag with either the mechanical or electrical differential, in so far as affecting the regulation?

L. W. W. Morrow: The object of all of these drives as outlined in the papers seems to be to answer the speed-regulation requirements in the production of paper. I should like to see something that would show the response of these drives to the actual requirements; in other words, if there is a change in load in any one section, what is the time interval until adjustment to that situation by the drive? Each drive has been described, but we haven't definite time data as to the results accomplished by the drive.

F. C. Bowler: We have heard a great deal about the exact regulation which will be produced by these various types of drives and emphasis has been put on the need of exact regulation. I presume that the authors have made some experiments tending to show what the actual regulation has been with the various types of mechanical drive which we have had in the past. I wish that might be brought out. In other words, it is a question in my mind whether we aren't putting emphasis on something that is more refined than we need. We have made paper a good many years with belts and gears, and personally I doubt if we have ever had such regulation with mechanical drives as any of these new sectional drives will give us.

N. D. Paine: I would like to agree with Mr. Bowler and say that we are inclined, perhaps, in the sectional drive, to attain too exact speed requirements. As he said, we have made paper for years with belts and pulleys, and now, with the electrical drive, it is more a question, especially on the large 234-in. machines, of starting the dryers than of the actual speed control.

We do get exceptionally good speed control with the mechanical interlock, of which our company has four on the 234-in. machines.

The papers lay quite a bit of stress on the fact that there is a large amount of stored energy in some types of motors. With regard to the mechanical interlock drive, that stored energy is used to very good purpose. The master shaft being driven from the dryer section of 34 6-ft. dryers, weighing 12 tons each, naturally maintains an extremely steady speed, as the energy stored in this section smooths out any slight speed variation which might occur due to small voltage fluctuations.

Coming down to the various section motors, I can say, especially on the couch—which we have watched more particularly —that speed control, where the paper is the weakest, with our Harland or mechanical interlock, is maintained with a small field variation, from 0.05 to 0.10 ampere, in the shunt field, which is with the machine running at 750 to 800 ft. per minute.

H. L. Sanborn: There seems to be a question as to exactly what basic principles the electrical manufacturers are endeavoring to correct with their electric drive.

Mr. Staege refers to a steel mill as having a very heavy load, which would not exactly apply to the electric drive. There is little comparison between the steel-mill and the paper-machine variable loads, yet a plugged calender will subject its motor to two and one-half times its starting torque, probably as great a variation as the steel mill when the ratio of power in use is considered. This and other inherent conditions peculiar to paper-machine operation produce a system of variables making load changes one of the big factors the electric drive is called upon to correct.

These load variables may be caused by mechanical conditions, vacuum changes on the wire, poor bearings, sections out of alignment, stock changes, clothing, etc.

We have in the Abitibi Mill at Iroquois Falls the Westinghouse electric sectional drive. We find it more reliable than our mechanical types after four years of operation. The whole machine has greater flexibility. The operating efficiency has increased and as a whole the close regulation tends to produce greater tonnage over the corresponding machines of the same size having mechanical drive. The breaks on this particular machine have decreased and there has been a reduction in repair labor and material.

In the main, however, I think, we have perhaps forced upon the manufacturer of electrical material a very severe problem, but you must endeavor to bear this in mind:—The paper mill has been running for years and years, as Mr. Bowler states, and the electric drive is endeavoring to take up these old-time conditions and produce results superior to the mechanical type of drive, without redesigning the paper machine to fit the electric drive.

Our sectional drive has accomplished this feat at the Abitibi mill and the average operating efficiency on our paper machine equipped with this drive, conditions being equal, has not been exceeded, and on the average has not been approached by either the mechanical or non-sectional electric-driven machines in our plant.

J. F. Rhodes: I think my two friends who have just spoken have brought up very important arguments. I believe the Mead Pulp & Paper Company put in two of the first drives.

I think the main object in the machine drive is to keep the sections together, that is, synchronized. With the old machines we had an engine that required steam pressure to be constant all the time. Then we depended upon the governor to maintain the speed. After the paper maker got his paper over the machine, he had nothing more to worry about unless his thickness changed or something caused a break.

As we get into the electrical drives the main thing seems to be to get away from the engine and the only problem left is to supply the steam for drying. However, paper makers feel that if anything breaks down it will do so at the weakest point. If these things become so complicated that a brush gives away or a contact goes, we have to hunt the trouble, and in the meantime we may have lost three or four hours of production. The old type of machine was so simple that almost any paper maker could very quickly find out what the trouble was and get started quickly.

In building a new paper mill I do not think there would be any doubt that he would adopt the extraction type turbine and put in the late type of electric drive, getting the one that was the simplest, and required the least amount of space, and of course the financial end would come in.

I think we should aim towards simplicity in choosing drives. I do not believe there is any change in the load of the machine after it is started and the paper is going over the machine perfectly. If there should be a break at the calenders there probably would be a change in load there for a while which would react back to the motor-generator set and that would in turn slow down, if it was not properly regulated, reacting back into the machine again, causing another break.

R. T. Kintzing: These papers are so broad in scope that they necessarily have devoted but a limited space to electric control used on sectional drives. Control designers should be credited with solution of the very difficult electrical problem of precise motor-speed regulation. I should like to point out a few of the other control features involved in this application, and also to supplement the statements made in some of the papers concerning the various types of speed regulators.

Starting, stopping and inching are the usual operations required in controlling the individual section motors. Certain sections are occasionally reversed, others are temporarily slowed down, and other motors start and stop simultaneously. Running-load conditions are usually constant. Starting-load conditions may be those of a friction load or those of a load having high inertia. The latter are the most difficult to regulate. Starting-load conditions on the dryer and calender section are unusually severe.

Individual resistor-type automatic starters having positive time-limit acceleration are best on account of starting from a bus, the voltage of which may vary over a broad range to provide for different machine speeds. Push-button-operated starters with motor-driven cam-operated accelerating contactors have proved

very satisfactory. Time-limit overload and low-voltage protection is necessary. Starting motors at full field strength is desirable to obtain high starting torque with minimum starting currents.

The armatures of the section motors are connected to an adjustable-voltage generator while their fields and the control circuits obtain power from a constant-voltage exciter generator. All circuit breakers, disconnect switches, etc., should be connected to interlock the two sources of d-c. power and prevent damage from incorrect sequence of operation. It should be impossible to energize the control circuit of any section motor unless all of the switches furnishing power to the motor circuits are closed. Opening any switch should immediately de-energize the control circuits of all sections depending upon power supply from that switch.

Auxiliary motors driving exciters or blowers for forced motor ventilation should have their control apparatus interlocked and connected to insure their operation when the power-supplying generator is started and to cut off the power supply in case of overload on these auxiliary motors.

The many panels necessary for controlling and regulating the required apparatus should be assembled into one switchboard which can be located remote from the heat, water and dust of the machine room and under the charge of authorized workmen.

In addition to the usual push-button stations for starting, stopping and inching the section motors and for changing the speed of the entire machine, there is furnished with the equipment described in Mr. Staege's paper a "Safe-Run" station for each section which permits the section control to be made safe when it is necessary to work around dangerous parts of the machine and which cannot be restored to the running position until unlocked.

Heavy dryer sections and calenders require starting torques many times in excess of the running torque, while presses and other sections usually are started at reduced load and do not need much more than normal torque to start. If the range of operating speed and voltage is broad, special provision must be made to change the value of starting resistors as the voltage changes.

When starting currents become large enough to overload the generator, and cause undesirable voltage variations, means must be provided to obtain the necessary torque without these objectionable features. Separate low-voltage generators for starting purposes, separate starting motors, and series-parallel controls are methods in common use. In the case of dryer sections geared together, satisfactory stable division of the load on the driving motors can be obtained by a proper design of the motor. Motors having good speed regulation are necessary, but these unfortunately will not ordinarily parallel with equal division of load. It has been possible by means of special windings to design motors which have excellent speed-regulation characteristics and at the same time divide their loads equally when geared together.

A successful speed-regulating system must have ability to hold constant motor speed in spite of the various causes tending to change it, must respond quickly enough to avoid damage to the partly finished sheet of paper, and must operate with a minimum of attention. If the regulator can make a change in field strength of sufficient magnitude, can make it fast enough, and can stop when exactly the right amount of change has been made, successful operation is assured. Ruggedness and serviceability must be obtained in the design to make it a commercial success after these fundamental requirements have been secured. The most important features of the regulator described by Mr. Staege is its ability to produce a perfectly graduated change in effective value of the field resistor by the simple method of intermittently short-circuiting resistor steps by means of a conductor having a variable width. Enough resistor steps can be used to give all of the regulating capacity ever needed. Unlike former systems, the amount of resistance is not limited by the master speed. Those sections having high inertia and requiring more gradual changes in resistance can be equipped with smaller-pitch screws. As a result it is not necessary to sacrifice regulating capacity on the high-inertia sections and the lighter sections can be made to respond more quickly. An infinite number of resistance values between maximum and minimum may be secured. The regulator is truly differential in action and must produce 100 per cent speed correction before its action stops. Mechanically the apparatus employed is simple and substantial. It is evident that this system possesses to a very marked degree all three of the fundamental requirements: capacity, quick response and smooth regulation.

E. F. Bearce: The sectional electric drive for paper machines has accomplished some very definite results for the industry.

In the manufacture of news print, this drive is especially advantageous since it permits of the high paper speeds with positive regulation. For the higher-grade paper manufacturer the drive has provided regulation of speed which is one of the important features required to get a sheet of uniform weight and caliber. These points of advantage are in comparison with the older methods of drives using a variable-speed back line in which the speed may be limited by belt or pulley design and the use of a variable-speed steam-engine drive having a regulation not less than three per cent.

It is also interesting to compare the cost of the sectional drive with the variable-speed drive using a back line, both as to first cost and maintenance. It has been determined that the first cost of the sectional electric drive is a little greater than the back-line drive, but is considerably more economical as regards maintenance.

The papers have brought out some very interesting points as to the details of construction and arrangement of the three different drives, each one having distinct points of advantage, and all three in successful operation in different parts of the country.

The manufacturers of this equipment are to be congratulated on the development of this drive as one of their greatest contributions to the advancement of the paper industry, and I am sure every paper maker is ready to cooperate with them in the continuance of their good work.

E. B. Wright: We operate seven machines; three of them are driven electrically by d-c. variable-speed motors through a line shaft with cone pulleys and friction clutches.

This type of drive works out very nicely, the regulation being good if the exciter voltage remains constant. The least variation in exciter voltage causes a change in speed of the d-c. motors.

A motor-generator set, with exciter direct-connected, is used to drive the variable-speed lines. This set takes its power from an extraction turbine, which when operating at maximum rating and extracting the maximum amount of steam, at times falls below normal speed, which affects the exciter voltage causing a variation at the paper machine.

I should like to ask the speakers how the cost of installing the individual drive compares with line-shaft drive in new installations, also how maintenance costs compare.

R. S. White: Mr. Wright mentioned a variation in speed of the prime mover causing a speed change on the paper machine. My experience has been the same.

We have a synchronous motor-generator set with exciter direct-connected. This exciter supplies the excitation to the d-c. generator as well as the synchronous motor. Therefore any slight change in speed causes a voltage variation in the d-c. generator due to the exciter voltage varying.

When first starting, we had considerable trouble with the governor of our turbine and consequently had all sorts of speed variations. Now if the paper-machine head box were set

for, say, 25-lb. paper at 300 ft. per min. and then the machine suddenly changed to 325 ft., it would cause the paper to drop in weight and change the dryness at the same time.

All paper-machine drives, in my estimation, should have voltage regulators to take care of just such trouble as we experienced. I understand that all Harland drives are now furnished with voltage regulators.

The Harland drive for our No. 2 machine has been in operation four months and the No. 1 machine two months. Outside of the trouble mentioned we have not any fault to find with the performance of the drives.

When we started the No. 2 machine we had a suction press roll 22 in. in diameter. Soon this was removed and a 26-in. rubber press roll installed. Since this roll was 4 in. larger, it had to run slower. Now the field rheostat or regulator did not have a range wide enough to cover this, so we had to change the gears and get a larger ratio.

It seems to me that these regulators should be designed to cover a much larger range than they do in our machines, as paper mills change managers and each one wants different equipment. And in order to drive this equipment extra gears must be kept in stock.

Mr. Norris mentioned something that seems to me is more important than close regulation between sections, and that is the control of the supply to the machines. Why not have the pumps interlocked so as to give uniform supply? If the supply to the machine is not fed on the wire at a uniform rate, the paper cannot be of good quality. There should be an automatic arrangement so that in case the machine changed speed, the opening from the head box (if a Fourdrinier machine) would change in direct proportion to the speed.

C. A. Farrell: We have all three drives, single-motor, sectional and mechanical. I guess the proof of the pudding is in the eating, and all of our machine men are unanimous for the electric drive. We find that they like the sectional drive the best, although I can't see but that we get almost as good regulation with the single motor. Of course, we have belt trouble. I notice that one of the manufacturers has a provision also, I think, in the face of the motor for cutting in some series windings. I would like to ask whether that is necessary on all of the sections or just a few, and whether it is for starting purposes only.

Mr. Norris says that he uses compound-wound motors, and the other manufacturers use shunt motors. I wonder if there is a reason for that.

I think our sectional drive was one of the first. Our motors are larger than necessary and we don't have any trouble from temperature, but I wonder if the motor is enclosed only to keep the water out of the machine or if they depend upon the forced air to keep down the temperature and therefore use a smaller motor.

I would like to know what sizes of motors are used in the drives today compared with ours. We have 35- to 50-h. p. motors, I believe.

We are particularly interested from the maintenance standpoint in the temperature of the motors. As large as our motors are, in the heat of summer they frequently run temperatures that are pretty high.

Tom Harvey: I look at this from an owner's standpoint. I am wondering if these people who put in these very expensive electric drives are getting a return on the money invested.

We have four machines making box board. I was very much disappointed that none of the speakers said a word on box board. Our tonnage amounts to the total tonnage of all of the news paper, all of the book paper and all of the writing paper made in the United States, and I think it should be recognized.

One of the authors shows a drawing of a cylinder machine and does not say a word about it.

We have one old mill that has been running about 25 years, and because of the crowding of the mill we decided some few years ago to electrify it. We have spent considerable money in that mill and I suppose it is electrified as well as any other boxboard mill with the exception perhaps of the mill at Ritman, Ohio.

We find that we don't get the return on the mill with the large investment that we do from the mill with the smaller investment. We also get much larger tonnage from the mill that is what I call directly driven from the steam engine with the rope drive. We have very little electricity in that mill.

I can readily see that the electric drive is a great advantage to the people who are making news paper and are running their machines up to a 1000 ft. a minute, but I have yet to be shown where a manufacturer is justified in spending the amount of money that he has to spend to put in the electric driven machine. I doubt very much if the stockholders would be satisfied if they could see the results from the machines that are not electrified.

J. H. Crossley: We have only just started up our first two sectional-drive machines, which are the General Electric Company's drive.

I should like to ask Mr. Norris what he means when he says that when their interlock is out of action, the wet end of the machine does not run wild? I am curious to know what would happen to our drive if our regulator should go out of action.

A. O. Spierling: I was glad to hear Mr. Harvey refer to the financial studies which must be made when considering the addition of electric drives to paper machines.

At the present time we, at Hammermill, are using the mechanical type of drive on each of our five paper machines. About four years ago we investigated the electric drive and have been giving considerable attention to it since. We credit the electrical manufacturers with doing a splendid piece of engineering work in perfecting the electric drive. Any of the three types of electric drive described, we believe, will work very well but their installation involves considerable expense which is sometimes very hard to justify.

We have thus far been unable to find how we could produce paper any cheaper by replacing our present drive with the electric type of drive.

There is one point, however, which has been brought out here at this meeting which if shown to be true would immediately touch any paper maker's heart and that is the statement that with the electric drive a better quality of paper might be produced. If this is true, the paper maker would be immediately much in favor of this type of drive because if he can produce a better quality of paper he can get more money for it and therefore justify the expenditure.

Of course, the thermodynamics of the matter enter very much into it, and it is a heat problem from start to finish. We charge against our paper machines the heat units that are used not only for the engine drive but also for the air that must be supplied to carry away the evaporated moisture.

Everything of that nature has to be taken into consideration before a person can say whether or not he is justified in putting in such a drive. It may, however, work out better with a new installation or with larger machines than it does with an existing installation of moderate-sized machines. Our machines are comparatively small compared to 300-in. machines. We manufacture a high-grade bond paper and run at speeds anywhere from about 100 ft. a minute up to 500 ft. a minute.

W. W. Spratt: One of the items touched upon is the heat balance of the paper mill. I believe it is an important subject to which we should give serious thought.

Mr. Norris, in his paper, mentioned that the 125-ton machine requires, roughly, 39,000 lb. of steam an hr. This, he estimates, is equivalent to 1000 e. h. p.

Let us assume that for the class of mills considered, power is worth from ½ to one cent a kw-hr. Mills having adequate hydroelectric development, principally in Canada, may,

of course, get power for less than a ½ cent. Depending on the cost of competing power and cost of coal in the district analyzed, it is estimated that it may be worth from $5000 to $25,000 a year as an incentive for the mill to obtain by-product power from this quantity of steam. Taking an average condition of $15,000, the average mill would hardly, under these conditions, utilize live steam through reducing valves to do the work in the dryers, which points out the importance of consideration of some sort of non-condensing or by-product prime mover as a source of power for the paper machine.

This is the question which I know Mr. Harvey, in his discussion, was referring to, especially in relation to board mills. I have seen many cases in board mills which did not have the best type of heat balance. Unfortunately, in the case of mills that do not have the heat balance worked out well, and are electrified, the story gets around that it is uneconomical to drive the mill electrically, while, with a much better heat balance, taking full advantage of the possibilities of generating by-product power, such a situation would not be so marked and the advantages of electric drive could well gap the difference of some of the losses on the pure question of steam utilization, as referred to the engine drive which unfortunately still predominates in board mills.

I believe the greatest advantage of a sectional drive is in a new mill where advantage can be taken of the smaller space and the basement can be utilized for other purposes. I know of one mill which installed sectional drive merely on the basis of lower building cost and other items which have not been discussed. They operate a board machine from 50 to 200 ft. per minute. Fortunately, they happen to be located where they can buy power from Niagara and they have a cheap power rate which assists them. Even in their case, however, there would be some advantage in using a non-condensing unit to drive the d-c. generator.

We have heard a very interesting discussion touching on the relative merits of moderate-speed motors versus direct-connected, slower-speed motors. The discussion took us into the question of stored energy of the different motors. We are chiefly interested, however, in maintaining the speed of the motors, whether we do it by means of an interlock system, synchronous-motor tie-in system, or regulator system. In this connection, I believe we all agree that the system with the maximum stored energy is less susceptible to speed changes. The stored energy tends to maintain the speed at the proper value. Our problem is one of maintaining the desired speed and a large stored energy assists us. It is only when we are away from the desired speed that a large stored energy would be a disadvantage.

I should like to ask two questions; one is with relation to the system utilizing the dryer sections as a master. I should like to ask why that is done, rather than having a regulator which is entirely independent of any one section of the machine.

I should like to ask Mr. Rogers how long it takes the vernier brush arm of the synchronous-dynamometer regulator to travel from one extreme to the other.

N. D. Paine: May I answer one of the last questions,—as to why the dryer section is used as a master section? I mentioned before that the immense amount of inertia in the dryers naturally tends to keep them at a very steady speed. As a matter of fact, using a Bristol tachometer which is extremely sensitive, we have found that when we had that tachometer on the master shaft, it would draw a straighter line than you could with a ruler for possibly four or five hours on end. It also obviates the necessity of using section regulators. You cut down your initial cost in that way.

It has been mentioned that when the dryer section is shut down the master shaft is stopped and the section motors are running wild. This is not correct. When the dryers are shut down, the section motors automatically go to the non-interlock point of the field regulator, which is only one or two commutator or face-plate segments away from the operating position of the regulator brush arm, and this position is less than 0.25 ampere in field-strength value. I happen to know that our own paper makers hardly realize that there is any difference in speed once we have our regulators set when the dryers are shut down. In fact, once the dryers are shut down, you are not making paper; you can't handle it the full width of the sheet; you can only take your lead strip up to the third press at most, so why worry?

L. E. Markle: It is common practise in paper mills to have the machine operating for 24 hours a day, over a period of six days in the week. In view of this continuous service, the mechanical duty required of the rheostat mechanism described by Mr. Norris as a breathing process must be rather severe. We should like to ask whether special precaution is taken in the selection of materials and the construction of the face plate and brush mechanism?

Several of the paper-mill representatives as well as the authors of all of the papers have emphasized the necessity for close speed regulation at all times. Since the permissible changes in speed are so small, it is certainly true that any system which will correct to a finer degree than other systems is desirable. All systems require some speed reference as a master. This unit may be a section of the paper machine such as the dryers, or it may be a unit driven by a separate motor. Since any change in the speed of the master unit affects the speed of the entire paper machine, causing it to speed up or slow down as the master speed changes, it would seem that an installation as described by Mr. Staege, where the speed of the master set is regulated just the same as the speed of any of the main driving motors, would naturally give a closer speed regulation.

I feel this point vital because as mentioned before the limits of permissible variation are small, and any system which can regulate better than another, no matter how small the amount, is preferable.

S. A. Staege: Mr. Rogers calls attention to the controversy on the relative merits of high-speed, medium-width machines as compared with medium-speed, very wide machines, and indicates that there is now a tendency to favor the former. A more complete statement would be to say that the high-speed, medium-width machine first reached its supremacy, but is now being followed by the high-speed, very wide machine, as there does not appear to be any fundamental reason why the very wide machines should not operate at equally as high a speed as the medium-width machine. Present practise indicates wider machines than ever built before combined with a maximum contemplated speed so far unapproached in actual commercial practise by several hundred feet per minute. The real limitations of the paper machine both as to speed and to width are determined by such factors as the maximum speed at which the sheet can be formed properly and by economic factors pertaining to the machine clothing, initial cost, etc., and not at all by the drive.

All available data confirm the indication that the power required by the several sections of the paper machine varies directly as the width of the machine and directly as the speed of the machine so long as the other relevant factors remain substantially constant.

I do not agree with Mr. Rogers' statement that the synchronous-motor tie-in system is a preventive and that the regulator type of control is a corrective system, nor am I able to agree that in the regulator type of control there is no restraining power to hold the motors in place. In fact, in the case of sectional drive, the d-c. motor has available a restraining torque equivalent to far more than the full-load torque of the motor, whereas, in the case of the synchronous, tie-in system, the full-load torque of the synchronous motor is far less than the normal torque of the d-c. driving motor. It is quite true, however, as Mr. Rogers has said, that the success of the regulator type of control depends upon the amount of angular dis-

placement which causes the regulator to function and by the time element of the motor field. This means that there should be absolutely no lost motion and that resistance be cut in or out of the motor field circuit with the smallest possible change in angular displacement of the motor. It also means that the time element of the motor field circuit should be as short as possible, which is inevitably associated with relatively high-speed motors.

I should like to ask Mr. Rogers if he does not feel that a speed change of a section of the machine of 0.15 per cent which he has indicated may result from a load change, in the case of the synchronous-motor, tie-in system, is not too much for satisfactory operation, particularly at the dry end of the machine. Personally, I feel that such an amount of speed change between sections is far in excess of safe or desirable limits.

In the case of the synchronous-motor, tie-in system, I should like to ask Mr. Rogers at what speed the frame of the synchronous motor is made to rotate by the small variable-speed, d-c. motor. It would appear that if the speed at which the frame rotates is a very small percentage of the rotor speed, then the change in speed of the small, d-c. motor might have to be several hundred per cent to accomplish a change in speed of the d-c., section-driving motor of, say, 10 per cent to compensate for possible changes in diameter of the roll, change in draw, etc.

I would also like to ask whether the paragraph in his paper immediately preceding the description of the synchronous-dynamometer type applies to the paragraph immediately preceding it.

From Mr. Rogers' conclusions, it appears that the three authors are now unanimously in agreement that regulator control best meets the requirements of sectional paper-machine drive.

It is stated by Mr. Rogers that the synchronous dynamometer regulator operates on an angular displacement corresponding to approximately 0.05 per cent change in speed of the controlled motor. Obviously, if there is a change in speed, the angular displacement will continue to increase until the speed is corrected and it would be desirable to know how long this 0.05 per cent change in speed must continue to obtain a sufficient angular displacement to operate the regulator.

It would be interesting to know through how many mechanical degrees the stator of the synchronous dynamometer would have to rotate to move the commutator rheostat brushes through 450 operating points. I should also like to ask what means are employed to actuate the brush on the large-step portion of the commutator rheostat. I should like to ask Mr. Rogers of what the anti-hunting features consist in the regulator equipment described by him.

Mr. Norris in describing the interlock regulating system states that in practise the brush arm quietly breathes between two contacts. I should like to ask the order of the frequency of oscillation for the various sections of the paper machine and the actual amount of angular displacement through which the d-c., section-driving motor oscillates in response to the resistance changes.

A statement is made by Mr. Norris that should the master section shut down, whether it is the dryer section or a small master motor, all the other sections automatically still continue to run at the speed at which they were first operating. I should like to ask through what means this is accomplished.

H. W. Rogers: In connection with Mr. Staege's paper, I would like to say that the General Electric Company installed and put into successful operation in 1909 a sectional paper machine drive with a definite tie-in between the sections.

Mr. Staege describes the synchronous tie-in type of drive and states that any change in load on the part of one section will affect the speed of the entire paper machine. In this connection, I wish to state that the use of synchronous motors on each section of the paper machine is analogous to a positive mechanical tie-in between the sections, and the machine operates as though driven by a single motor. Therefore, the effect on the total load of a change in load on one section is a matter of two or three per cent and the effect on the speed of the machine as a whole for such a change in load is less than 0.1 per cent.

After describing the improvements which have been made in the synchronous tie-in type of drive, Mr. Staege states that the effect of speed variation in the small d-c. motors which rotate the synchronous-motor stator frame on the main driving motor is approximately inversely proportional to the ratio of the worm gear used in driving the stator. This statement is incorrect inasmuch as the gear ratio has nothing whatever to do with the speed regulation of the d-c. motor. A small d-c. motor drives the synchronous-motor stator at a speed which permits of proper draw adjustment, this speed being only a small percentage of the speed at which the main motor is operated. Therefore, any variation in speed of the small motor directly affects the speed of the stator, but the stator speed being a small percentage of the rotor speed, its effect on the main driving unit is inappreciable.

In my experience I have found that the control of the high-speed machine is the simplest problem with which we have to contend and that the low-speed and wide machines present the greatest difficulty.

I am interested to know just where the third type of regulator mentioned by Mr. Staege is in operation and on how many machines. I should also like to ask what provision is made to eliminate a so-called wild machine when the master set is shut down.

The European drive to which Mr. Staege refers on the ninth page consists of a-c. commutator motors and has been in successful operation at the Empire Mills, Ltd., for practically two years and is now being followed up by a second installation in another mill.

S. A. Staege: I think there is some misapprehension as to the effect of inertia in the moving system with respect to the regulation of the paper machine. As Mr. Spratt indicated, where there is considerable flywheel effect, regulation is frequently easier than where there is very little. I might say that in respect to the dryer sections where there is a very great amount of flywheel effect, the rotary-contactor regulator which has been described is able to take care of the regulation just as completely as on a press section where the inertia is almost negligible. In fact, I am unable to see that the amount of flywheel effect should seriously affect the regulation of the paper machine. The amount of stored energy in the motor is so small compared with the inertia in the dryers that I look upon it as a very small factor. It is perfectly true that if there is lost motion then a large amount of flywheel effect is undesirable; in fact, it is difficult if not impossible to regulate if you have lost motion in the regulating system. It is of course true that the high-speed motor does have more flywheel effect than a low-speed motor.

The speed of the motor field is the next controlling factor, providing the regulator works instantaneously. The rotary-contactor regulator's movement is absolutely synchronous with the change in angular displacement. The only possible chance for any delay in the corrective effect is in the time element of the motor field, and with the high-speed motor the field is very quick as compared with the field of the large slow-speed motor where there is much more iron and turns and the inductance is a great deal more. The response of the armature current will follow with practically no lag as soon as the field is changed.

I am not able to follow Mr. Rogers in his conclusions that the field is not a controlling factor in the time element of the motor.

The magnetic contactor is a very reliable piece of apparatus. When the contacts are made they rub and roll together, presenting changing surfaces, and the contacts never blister nor accumulate dirt.

Mr. Montgomery inquired as to the degree of regulation required, mentioning 0.1 per cent, and asking whether that was necessary. On the wet end of the machine, between the couch and the first press, the machine can stand considerably more than 0.1

per cent variation without breaking the sheet or causing any very serious consequences. I feel that any change in speed, however, tends to weaken the sheet although it may not be very serious. Farther on toward the dry end of the machine, a variation of 0.1 per cent would cause very serious straining of the sheet and between the dryer and the calender an elongation of the sheet of 0.1 per cent would almost certainly break the sheet. There are some grades of paper, of course, that have more elasticity than others.

The differential accumulative effect referred to which applies to both mechanical and electrical differential devices is accumulative in characteristics. If there is a change in speed, no matter how small, as long as it is allowed to continue the angular displacement keeps accumulating. And the accumulated value of departure, if it is attached to something which is supposed to regulate, will become greater and greater until the required action has taken place. The rapidity with which the corrective effect will be brought about is dependent upon the relations between the various parts, gear ratios if it is gears, or some other similar factors in determining the speed at which the secondary movement takes place.

Mr. Bowler called attention to the degree of regulation as compared with that of the mechanical drive. As brought out in these papers, mechanical drives are subject to belt slippage, and it is very well known that belts are liable to slip anywhere from a small fraction of a per cent to two or three per cent, depending upon the loading or condition of the belt, the arc of contact with the pulleys, the tension and numerous other factors. Of course, the amount of belt slippage, other things being equal, is nearly a straight-line function of the load transmitted, and if the total slippage, for instance, is two per cent under full load, a change in load of 10 per cent could be expected to produce a variation in that slippage of 0.2 per cent. However, a little moisture on the belt is likely to cause variations in the slippage of considerably larger values. It is the variation in slippage which affects the draw rather than the total or base slippage. If the drives all slipped exactly the same amount and never changed, you would have just as good a draw as though they did not slip at all.

Mr. Paine speaks of starting the dryers and comments on the stored energy. It is true, as I have indicated, that there is a great deal of stored energy in the dryers and they have to be started more slowly than the other sections of the machine. But if the proper time element is given they should be brought to full speed and synchronized with the control system without any difficulty. And where the regulator is designed in such a way that it starts up with full field on the motors and then after the motor gets up to nearly the operating speed the regulator gradually cuts in the field resistance, bringing it up to regulating values, there is no shock brought about and nothing to start oscillations. Of course, if you cut in the regulating resistance suddenly in the full amount, it is possible, if it is too much, to start oscillations of the dryers which might not easily be damped out, but when the resistance values are of the correct amount and the speed at which it is cut in properly controlled, there is no difficulty.

However, it is true that on the dryer sections with large inertia, the steepness of the regulation curve should be less than on sections with less inertia, because they cannot respond so quickly. You have there not only the lag of the motor field, but you have the inertia lag of the rotating mass, and the speed of cutting in the resistance must be adapted to the torque the motor is able to develop and to the inertia of the system.

Mr. Sanborn speaks of sudden variations and overloading conditions. The rotary-contactor regulator, which has been discussed by me, is designed to take care of any changes in load from no load to 50 or 100 per cent overload and still maintain the draw, and it does it. It has enough resistance and cuts it in at a sufficient rate to prevent more than a transient change in speed. That differs from the earlier types of regulators in which there was not a sufficient amount of regulating resistance to take care of such wide changes and in which it couldn't be cut in fast enough to overcome the initial tendency to drop off in speed faster than it could correct it.

Mr. Rodes mentioned the possibility of the brushes breaking on the regulator. If a brush should break or a wire should break in the rotary-contactor control, which is nothing more than a rheostat in which every step is divided into an infinite number of small increments of resistance, all that would happen would be that the drum would move longitudinally on the shaft a small fraction of an inch. In fact, if you were to lift out one brush while running the drum would move up about 1/16 in. and present the next step, and you could take out a number of steps of resistance or cut the wires, and it would simply move up far enough to compensate for it. You would hardly see any change in the draw at all; probably you wouldn't see any.

The simplicity of the sectional drive is not fully appreciated by most paper-mill people. Electrical apparatus has been so standardized and used so long that there is no uncertainty about its performance. It will probably stand up and give good service as long as any kind of mechanical device with similar treatment. And the records show that the maintenance is extremely low, something that cannot be met or even approached by most mechanical drives. As an illustration, one drive, of which a record was sent to me recently, has been in operation just one year, and had a total maintenance expense of $21.

Mr. Bearch questions whether there is too much refinement. I believe as long as we can get refinement without complication we ought to have it.

Mr. Harvey has raised a very interesting point in regard to cylinder machines. We have sectional drives on two-cylinder machines and they are giving a very good account of themselves. The maintenance is negligibly small and the power used is about 50 per cent less than where mechanical drive is used.

The draw can be controlled with greater precision with sectional drives than with any possible mechanical drive. And it can be held where wanted.

H. W. Rogers: In answer to Mr. Staege's reference to my statement that "the speed regulator which will best satisfy the exacting conditions of operation and appearance is the synchronous dynamometer regulator," I might say that this refers only to the regulator type of drive and its latest development. The statement has no reference to the synchronous tie-in type of drive which is being furnished and will continue to be furnished for some applications.

These two types of drive are fundamentally different; they each possess certain advantages and are both successful drives and yet they cannot be considered in the same class.

The question of torque available in the motors for maintaining constant speed under varying load conditions has been brought up. It is evident that the main driving motors have an abundance of it, whether slow-speed or moderate-speed motors are used. With the synchronous tie-in type of drive the restraining power is in the synchronous motors which have 20 per cent of the main motor capacity and have a pull-out torque of 200 per cent; consequently, they will hold the speed constant within a 40 per cent change in load either as a motor or as a generator, which is well within the load changes encountered on a paper machine. With the regulator type of drive the restraining power must come from the main driving motor and it is simply a question of whether it is instantaneously available for maintaining constant speed.

Both slow-speed direct-connected motors and moderate-speed geared motors have been successfully used on paper machines, but in my experience the purchaser has shown a marked preference for the slow-speed direct-connected motor. No difficulty has been experienced in designing either type to meet the requirements and it has been largely a matter of balancing the lower maintenance of one against the lower first cost of the other.

The moderate-speed motor will not respond more readily to changes in field strength than the slow-speed motor nor will it give a greater amount of torque for starting heavy loads. Slow-speed motors with good regulation can be made.

The slow-speed motor has a heavy armature with comparatively large WR^2, while the moderate-speed motor is of small diameter with a low WR^2, and while this might appear as an advantage to the moderate-speed motor, the truth is that we are not particularly concerned with the WR^2.

The stored energy in the armature is, however, of vital importance and is a direct indication of the ease and rapidity with which the motor will respond to the regulator and to changes in field. Since the stored energy in the armature is proportional to the square of the speed, it increases very rapidly in the higher speed motor, in spite of the smaller WR^2, and is many times larger in the moderate-speed motor than in the slow-speed motor.

As a further comparison the torque required to bring the motors to full speed in a given time may be of interest. Here again is a direct comparison of the responsiveness of the slow-speed motor and the moderate-speed motor, and while such wide changes in speed are not to be encountered, the comparison holds true for any percentage change in speed.

The moderate-speed motor has fewer armature conductors and a lower armature reaction; it also has a much lower inductance in the field than the slow-speed motor. The field, therefore, should and does respond more quickly to changes in current but that question is beside the point. What we are primarily interested in is the rapidity with which the armature responds to field changes and that is an entirely different question. The advantages are all with the slow-speed motor, and in the nature of things the field of the moderate-speed motor must of necessity respond about six times as rapidly as the slow-speed motor field to be on the same basis. This is not the case, but if it were possible the moderate-speed motor would still require many times greater change in armature current to produce the same responsiveness in speed, as the slow-speed motor.

It is well known that where rapid cycles and quick reversals are required, as in rolling mills and some machine-tool applications, the moderate-speed motor is always abandoned in favor of the slow-speed motor. The most important example of this application is the high-speed elevator which is driven by the slowest speed motor (65 rev. per min.) to secure sensitive control and quick response.

As regards regulation, it should be sufficient to state that hundreds of motors have been built at speeds from 38 to 100 rev. per min. with practically flat speed curves.

The slow-speed motor not only has as much torque as it is possible to obtain from any moderate-speed motor, but it has more active material and a much greater heat-storage capacity. It will stand greater overloads and more punishment without ill effect than the moderate-speed motor.

In first cost the advantage is with the moderate-speed motor, but in all other respects the advantages are with the slow-speed motor which may be summed up as follows:

1. The slow-speed motor has a much lower stored energy.
2. It requires less torque to produce a given change in speed.
3. The armature will respond more quickly to field changes.
4. It has a greater heat-storage capacity.
5. It will stand heavier overloads and more punishment with no ill effects.

In his remarks justifying the use of moderate-speed motors, Mr. Spratt has stated that heavy inertia or large stored energy is an advantage in maintaining speed, whereas Mr. Staege has admitted that the dryers, which have a large inertia, are more difficult to control since they do not respond quickly to changes.

The stored energy of a couch or press section may approximate 29 or 30 kilowatt-seconds, whereas the stored energy of a slow-speed motor armature is probably not more than one-quarter of it. The stored energy of the modertate-speed motor armature is probably two and one-half times that of the couch or press section and constitutes the bulk of the stored energy involved.

Mr. Paine has suggested the use of the dryers as a master. This is a practise that has been followed extensively on news machines and other machines with a narrow speed range and I can see no objection to it. It simplifies the control somewhat and does not affect the speed of the other sections when shut down as the regulators retain their operating position.

On wide-range machines, however, making book kraft or heavy papers, there is a tendency for the calenders to pull the dryers ahead and change the speed of the whole machine. Consequently a master set is a decided advantage in this case.

Several discussors have intimated that perhaps the electrical manufacturers are striving for unnecessary perfection and Mr. Montgomery has asked what regulation is actually required. In actual tests on mechanical drives I have found the regulation between sections to be as high as 1.2 per cent without affecting the operation of the machine or causing any complaint, and while I do not think that this should be taken as any criterion, it does indicate that exact speeds are not absolutely essential. Any of the sectional drives thus far developed will maintain speeds far beyond the possibilities of any mechanical drive.

All of the regulators described are synchronous in type and operate on the principle of an angular displacement between the two elements, the successful operation depending upon the magnitude of the displacement which causes the regulator to function. With the synchronous dynamometer I have described, a displacement of one-quarter of a mechanical degree or less between the stator and rotor will cause the stator to move and the movement ceases when the angular displacement disappears. Under these conditions there is no cumulative effect as is common with a mechanical drive. We have made no oscillograms of the synchronous dynamometer regulator, but from close observations I have made it seems to respond instantly to changes in load such as are normally encountered on the calender. Under normal conditions of operation the vernier brush on the upper half of the commutator rheostat will have sufficient range to meet all requirements but for extreme load changes the lower brush, which operates on coarser resistance steps, comes into play. This lower brush is carried on a yoked arm between the yokes of which the vernier brush moves and until the vernier brush has made its complete travel, the lower brush does not move.

All of the regulators described operate on the same fundamental principle of shunt-field control; they all operate on the basis of an angular displacement between the two elements and it is simply a question of which one operates on the smallest displacement, and which one is the simplest mechanically and electrically and has the lowest maintenance.

Mr. Harvey has requested information regarding the cost of sectional drives and I might answer him by stating that, where a new machine is involved, it is always possible to justify the sectional electric drive over a mechanical drive with either single motor or steam engine.

The use of auxiliary series fields on the dryer and calender motors was practised to a certain extent on some of the earlier drives, but at present we use shunt characteristics on both motors and generators with saturated fields on the dryer and calender motors for starting.

The use of enclosed motors is dependent upon the wish of the purchaser, but in no case do the enclosing features affect the temperature rating nor are such features ever used to justify smaller frames.

R. N. Norris: Mr. Montgomery asked a question on the degree of control—was 0.1 per cent sufficient? I think that a little better than that is necessary. So far as I can see from measurements taken personally, the average we have got can be taken at 0.03 per cent. That is from very careful measurements taken over a period of years.

I don't think there is anything in the accumulative effect. I agree with Mr. Rogers in that.

Mr. Bowler referred to the exactness of regulation on mechanical drives. I think Mr. Staege replied to that in what he said about belt slip. I don't think I need to say anything more about it, except to say that Mr. Bowler is quite right when he says that for years paper makers have made paper on mechanically driven machines satisfactorily. That is perfectly true, but then, of course, we reached a stage in paper machines where they became bigger and they have to be operated at much higher speeds, and the increased speed necessarily led to the development of these sectional drives which, once developed, proved to be far superior to mechanical drives in several respects.

Mr. Paine referred to the question of using the dryer section as the master section, and Mr. Staege also made a comment on this point. It is of course perfectly easy for dryer sections to be controlled. It is not at all a question of not being able to control them. It is purely a question of convenient arrangement of the plant.

It is often of considerable advantage to use the dryer sections, which are heavy and have considerable momentum, as a means of giving steady speed to the master shaft. If it is desired to control the dryer section it can be easily done. But why do it if it is not necessary? Why not simplify the equipment? That is one of the things at which we have aimed, namely, simplification in construction and installation.

If, however, it is required to control the dryer sections, as is advisable on book machines, kraft machines, tissue machines, etc., etc., then all that is necessary is to drive the master shaft with a small master motor and interlock the dryer sections to that. As a matter of fact there are in operation in Canada three interlock drives so driven and two in England, the two in England being big newsprint machines and the three in Canada being smaller book machines.

I agree with Mr. Rogers that for the high-speed news machine the drive of the master section by the dryers is all right, but for book machines, kraft machines, and tissue machines, it is questionable, and my inclination is to have the master motor for driving the master shaft, and not to drive from the dryer section.

Mr. Sanborn asked what the basic principle is that we are endeavoring to correct. We are of course endeavoring to correct the degree of variation in angular movement of paper-machine rolls, and the amount of load variation we are endeavoring to take account of is the normal load variations which occur on a paper machine.

I agree with Mr. Staege that he average conditions of load on a paper machine do not vary very considerably and are nothing like as heavy as the load variation that will occur on, say, a heavy rolling-mill plant. I have seen, however, fairly large load variations take place over a period of time. I have seen a couch motor, for instance, taking as a normal load 125 h.p., go up quite unexpectedly to 160 and 170 h.p. without any apparent reason. The reason of course was something mechanically wrong in the bearings or the Fourdrinier part of the paper machine, or possibly increased suction, but with the interlock system the design of the equipment is such that we provide sufficient control and resistance to deal with very heavy overloads and to prevent suctions dropping out of step. In fact we can comfortably handle overloads as high as 200 per cent if desired. If you put into your control the extra ability to compensate for these big changes in load then it is an additionally desirable condition to have.

One discussor referred to the question of starting motors on full field. That of course we always do; in fact the motors are started on what we call "super-field," as they have the full normal shunt excitation and they have the additional heavy series turns in operation at the same time.

Another gentleman referred to the question of maintenance costs on the regulator faceplates and brush arms. All I can say in reply is that we have over 30 machines in operation in Canada alone, and we have not yet been called upon to supply any spare contacts or brush arms for these regulators. We have supplied, I think, probably along with the installations as spares, some new faceplates, and probably clients have put them into operation, but we have not known of it, nor have we ever been called upon to replace them. In fact, the amount of wear on the faceplates is practically nil. When we first went into this question in 1912 and 1913, this question of wear troubled us also, but the large equipment we installed in 1913 is still running with the original faceplates, and this question of wear on faceplates need not be taken into account.

In relation to the question of the use of direct-coupled motors of slow speed as against higher-speed motors geared to the sections, I can say that we are perfectly content to use either, and have used both with perfectly good results. All our motors are compound-wound, and the results obtained prove that the compound motors are quite capable of giving the service, and of dealing with the heavy starting torques without the necessity of inching motors. As a matter of fact I think it is one attribute to the interlock system that it will control large slow-speed compound-wound motors very satisfactorily.

Mr. White referred to an installation that had no voltage regulator. I agree with him that one is essential, and on this particular installation, I had recommended that this voltage regulator be installed. On the whole I believe voltage regulators do improve operation, but we have had some extraordinarily good results without voltage regulators. The Laurentide machines, which have operated over 1000 ft. per min. since August 1921, have no voltage regulators and I say without exception that the machines are among the safest in existence today.

The question has been asked as to the amount of draw control that can be allowed at each section to compensate for the change in roll diameter from, say, 22 in. to 26 in. This is entirely one of previous decision in the design of the equipment; usually, we allow 20 per cent, but if somebody wants 50 per cent it can be given. If they want to make the equipment so that they can change rolls with ease, it can be given. The average paper machine does not need such a condition as this; in fact, I think it is the first time that I have ever heard of such a condition as this being required.

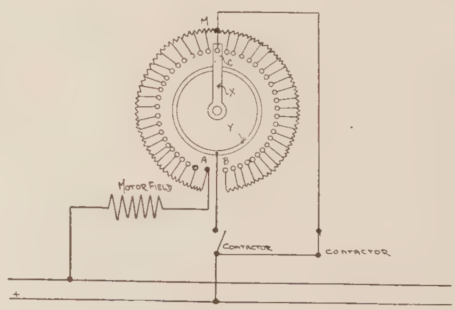

FIG. 1

Mr. Harvey referred to the question of finance and the application of the drive to the cylinder machine, and made the statement that he did not see where the increased cost of the sectional drive warranted its installation on book machines, or how its installation was warranted in taking out an old machine and replacing it with a sectional type.

I think the question of the cost of the drive is bound up with the results one can get. We have installed drives on book machines which have given so much satisfaction to clients that they say the installation is more than warranted by the results they have obtained.

Of course, where the book machines are going to be operated at higher speeds, sectional drive is the only thing. We have book machines on order today that go up to 850 ft. per min. I received an order recently for one book machine which is to have a speed variation of from 150 ft. to 850 ft. That is to be 170 in. wide, which is a pretty big book machine.

Mr. Crossly asked what I meant by saying that the machine was not "wild" when a certain master section was shut down.

This can be explained by reference to the accompanying diagram, Fig 1. A is the full field position; B is the weak field position with all resistance of the regulator in circuit. C is the normal working position of the arm. The arm X makes contact from Y ring to contact C through the carbon brush. Possibly C may vary one contact or two contacts, as the case may be, but it is only a very tiny bit and gives only a very tiny difference in field current.

When the master section shuts down the arm, X travels around, but the connection from the $+$ busbar to Y is broken by an automatic contactor operated when the dryer motor is shut down, and, in place of the connection being made through the ring Y and arm X to the point C, connection is made through another contactor to what we call the "mid-point" M on the resistance itself.

As a matter of fact the two contactors are combined in one, one of which opens, and the other closes, when the dryer motors shut down.

The resistance connection M is adjustable in the right working position for the paper machine, and it is found that this always remains in about the same position, no matter in what position the paper machine is working, as the equipment is designed to operate at the same field current on high-speed machines all the time. Where variation of field current is required for wide-range machines the motors are designed so that, by the alteration of one combined rheostat, all field currents are operated at the same time in the same degree, and the arm remains in the same position.

I think the above remarks also apply to Mr. Staege's question as to what happens when the master shaft shuts down.

One gentleman referred to the question of thermal conditions in the mill. This opens up a very interesting phase of the whole subject of sectional electric drive, and one to which I have given a little thought, of late. It is a very interesting study, and I say that by the use of sectional electric drive it is possible to obtain a better heat balance than with any form of mechanical drive. My reasons for this statement are too long to enumerate here, but it is a subject which deserves considerable investigation.

One gentleman raises the question of carrying the paper through to the third press if the dryers are shut down. This is not an important matter in spite of what some paper makers may say, because, if you shut down the dryer sections for anything at all, it means a stoppage of several minutes. During this time, much the best place to let the paper go to is the pit at the couch, and, as a matter of fact, there has lately been installed in the mills of the International Paper Company at Three Rivers a device that, when the paper breaks at any section of the machine, will automatically break the paper at the couch. I think this is good practise.

Mr. Staege asked the order of frequency of oscillation for the various sections of the paper machine. The frequency of breathing of the regulator arm is an absolutely mechanical reflection of what is happening in the paper machine room, and it is therefore possible to count the oscillations and the time period in which they take place with the interlock equipment.

A feature which is of considerable assistance to the paper maker is an indication that the sectional drive is working satisfactorily. I would not call this oscillation; in fact there is no oscillation. The arm breathes quietly—and I emphasize "quietly"—from contact to contact, often taking a very considerable period of time to do it; in fact, I have personally sat and watched the arm work without seeing it move an amount appreciable to the eye, for over a quarter of an hour.

The average speed of movement over the working range of the arm, under normal operating conditions, varies a little, but when it is calculated into items of percentage of the variation in feet per minute of the paper, it works out, as I previously said in reply to Mr. Montgomery, to the order of 0.033 per cent.

Mr. Staege, in his description of the interlock drive, I think, has quite inadvertently used the past tense in reference to many of his verbs, when he says that the dryer shaft "was" driven, etc., etc.; and all I can say is that the present tense is more applicable, as the drives not only "were" working satisfactorily, but "are" working satisfactorily, and "will" in future work satisfactorily.

Then there is the question of this "backlash" which he visualizes, and this elastic master shaft, and with all this "backlash" and "elasticity," it is a wonder that the interlock drive has been able to do anything at all. But facts show that it *does* do it, and does it with remarkable success, and today holds unbeaten records for output in the way of tonnage on the machines, one machine having produced as much as 127 tons of newsprint in 24 hours, and having given an average, over a period of months, of 114 tons per day.

Furthermore, the average highest operating speed is held by the interlock, since August 1921, on the Laurentide machines.

Mr. Staege, in his description of the new system, uses the word, "automatic" regulation. I do not quite see how he claims that this is automatic. The regulator in itself cannot change the field, and the multiplicity of contact which he refers to is an endeavor to get slide-wire effect, but in my opinion is not necessary.

It is that which is at the back of the regulator which does the work, that is, the screw in the worm, which is in the nature of a mechanical differential, and I do not quite see how Mr. Staege can claimthat this entirely is an electrical differential.

I refer again to the question of having something in our equipment which the naked eye can see is happening, which is an instant reflection of what is happening on the paper machine roll, and that is the movement of the regulator arm. It doesn't matter whether you have 10 ohms in between stops, or 1000 ohms,—as long as the arm is only moving a short distance, it is an inner mechanical connection back to the regulator, unless the belt is slipping, and if the belt slips you couldn't make paper. There is something which is a mechanical indication to the eye independent of time lags of field, independent of back lash, independent of elastic shafts.

The question of the vernier on a rheostat is a matter of opinion, I think. Mr. Rogers described the interesting vernier they have employed on their regulator type. I think it is quite good. As a matter of fact we had also a vernier once upon a time, but we didn't carry it any further. We thought it was an additional complication, and we left it out.

Mr. Rogers referred to the question of the master shaft driving the high-speed machine. He says he has no objection to that. I quite agree with him. I think it is quite a sound scheme. If anybody insists on regulating it, it can be regulated.

On book-paper machines and kraft-paper machines I agree with Mr. Rogers that the calender can pull round the dryers through the paper alone. I have one kraft machine in mind which has a 75-h.p. motor on the calender and two 75-h.p. motors on the dryer. I have seen the calender pull 125 per cent full load, and the dryers practically no load.

We had another very interesting study once when we tried to drive a Harper machine. First, it gave us a lot of trouble simply because we did not appreciate (not being papermaking engineers) the conditions of a Harper-machine wet end. This machine has interconnecting felts between the couch and the first press, and the first press and the second press. The felts actually acted as belts and one would find that first, the press

motor was pulling the couch motor round as a generator; and then the couch motor would pull the press motors round as generators, depending upon the tension of the felts. Having discovered the difficulty, alterations were made within twenty-four hours, which enabled the machine to perform under all conditions required of it, and it is today running with absolute satisfaction.

A reference has been made by both Mr. Staege and Mr. Rogers to a new drive at the Empire Paper Mills in England, using a-c. commutating motors. This drive works, but it is very complicated and occupies a large amount of space.

Discussion at Madison

SOME INTERCONNECTED-SYSTEM OPERATING PROBLEMS[1]

(Boyce)

Madison, Wisconsin, May 7, 1926

D. W. Roper: In Fig. 3 of the paper, the greatest reduction in the operating troubles is the reduction in the interruptions due to lightning. I would just like to ask Mr. Boyce how these reductions were brought about and to what extent the reductions shown were due to reduction in number of, or severity of, the lightning storms.

Carl Lee: In referring to chart No. 3 and Mr. Boyce's reference to that, there is one point that I don't believe was touched on; that is whether or not insulators are changed while the line is hot or whether the line is killed in changing insulators.

Carl Dodd: Some companies have constant average frequency control. What effect would that have on large interconnected systems? Would it be possible to have constant-frequency control, either automatic or manual, at any or all of the principal stations, and keep the system in step?

L. E. Frost (communicated after adjournment): Mr. Boyce's statements about the division of load between generating plants are applicable only to rather special conditions of generating-plant development.

Obviously, the use of hydroelectric plants for only the peak load of the day and operation of steam plants continuously at efficient loadings is a process desirable only on systems where the hydro plants are large in proportion to stream flow. It would not be economical to design hydro plants for this type of operation unless the cost of extra pondage and extra hydroelectric generating capacity compares favorably with the cost of equal steam-plant capacity, taking into account differences in operating cost.

May I call attention to the fact that in dividing load between any steam-driven units which are in operation, the loading of each machine at its own most efficient operating point does not necessarily result in the greatest possible over-all economy for the whole group.

As an example, let us suppose that we have two steam turbo generators side by side supplied from the same steam header. One has a capacity of 20,000 kw. with its best water rate at 15,000 kw.; the other is a 40,000-kw. unit with its best water rate at 30,000 kw. Suppose that for some reason the load assigned to these two machines is 45,000 kw. At first sight it may seem best to put 15,000 kw. on the smaller machine and 30,000 kw. on the larger, thus running each at its most efficient point; but as a matter of fact, if one machine has a water rate much better than the other (as is often the case) it may be more economical to carry a larger portion of the load on the more efficient machine. Even though this decreases the operating efficiency of each machine individually, it may improve the efficiency of the pair as a whole.

To secure the very best economy possible we would want to continue the increase of load on the 40,000-kw. machine (and a corresponding decrease of load on the 20,000-kw. machine) to the point where an additional kilowatt would add no less steam to one unit than it relieved from the other.

1. A. I. E. E. Journal, May, 1926, p. 462.

Mr. Boyce's scheme of a load-limiting device set so as to secure the best possible efficiency from each individual steam turbine may be excellent if all units in operation are capable of about the same efficiency, but it is open to question if there are appreciable differences between the efficiencies of the various units.

F. G. Boyce: Regarding Mr. Roper's question concerning the graph on lightning, the reduction shown is not what you would probably think it is. It is not entirely an improvement in lightning protection. In 1920 our system was quite badly overloaded and during lightning storms, trouble on one transmission line would sometimes require that other lines be taken out of service due to lack of capacity. Correcting this condition represents part of the improvement shown, the balance being an improvement in lightning-arrester design.

We had quite a little trouble with electrolytic lightning arresters at that time and had to increase the insulation at the horn gaps and under the tanks. During this period I believe the lightning arresters caused about as many interruptions as they prevented. Since 1920 the arresters have been entirely rebuilt which has assisted in reducing interruptions due to lightning-arrester failures.

In the other portion of this graph classed as equipment defects, I think the greater portion of the improvement shown is due to improvement in quality and the use of a great quantity of insulation.

In answer to the question concerning the testing and changing of transmission line insulators while hot, we do not do very much of this kind of work, although we have used the buzz-stick method of testing insulators and have changed insulators while the lines are alive by the use of "hot-line tools." We now use the 60-cycle over-voltage method of testing insulators, changing the entire string of insulators when the line is dead.

In answer to the question of frequency control, we operate the system by means of Warren clocks. As seen from the map of the system, it is controlled from three points by means of system operators, one group at Saginaw at the lower end of Saginaw Bay on the east side of the state. These men are in touch with all plants in the north and from there south as far as Owosso. At Jackson there is another group of system operators who control the system south and west as far as Kalamazoo, and still another group of system operators who control the operation of the western portion of the system. The control is all centralized at Jackson, at which place the chief load despatchers are located who supervise the work of the system operators at the other locations. When the system becomes split, the system operators are in supreme control of their separate districts until the system is connected together again.

In answer to Mr. Frost, I would say that the combination of steam and hydroelectric plants in one system allows the most effective use of the kw-hr. capacity of the hydroelectric plants and that the load factor of the various units can be improved even with plants having moderate ponds; thus for a lower investment per kw. of installed capacity, a greater kw-hr. output can be obtained.

Regarding the operation of steam plants in combination with hydroelectric plants, it is possible to improve the load factor of the units in operation. An interconnected system permits the operation of units in the manner that Mr. Frost suggests, and is the way the operation of the system mentioned is usually carried out, namely, having units at their most efficient point at all times with reference to the rest of the system.

BEHAVIOR OF RADIO RECEIVING SYSTEMS TO SIGNALS AND TO INTERFERENCE[1]

(Peters)

Madison, Wisconsin, May 7, 1926

Edward Bennett: In order to appreciate the significance of the point of view which has been developed in Professor Peters' paper, it may be helpful to review the sequence in which the knowledge of the properties of circuits has developed. Practis-

1. A. I. E. E. Journal, August, 1926, p. 707.

ing engineers were first confronted with direct-current problems, and quickly obtained a very good understanding of the properties of complex networks or combinations of circuits, provided the problems related only to the steady flow of continuous currents in the networks.

Somewhat later came the realization of the possibilities of alternating current in the distribution of power. Engineers then became concerned with the performance of circuits when carrying alternating current. That situation was cleared by the adoption (largely through the writings of Steinmetz) of the method of the complex algebra for the calculation of the properties of alternating-current circuits.

In recent years, with the development of radio telegraphy and telephony, and with the development of extensive high-voltage transmission systems, engineers have become concerned, not so much with the performance of networks when carrying alternating currents in an undisturbed manner, but with the performance of these networks when they are subject to switching operations or when they are subject to disturbing electromotive forces,—the static impulses and so on.

Mr. Peters has developed and illustrated the application of the point of view that when we want to determine the effect of a transient disturbing electromotive force upon a receiving network, we may do this by replacing the transient electromotive force with the electromotive forces of suitably selected alternators which are conceived to remain in the circuit from the beginning of time to the end of time, and by calculating then the power delivery of these alternators to the receiving apparatus. The problem in the calculation of transient currents is thus reduced to the problem of calculating the steady-state values of alternating currents,—a calculation which is widely understood. It seems to me that the spread of this point of view will do for transient-current calculations what the spread of the method and notation of complex algebra did for the calculation of the steady-state values of alternating currents.

ILLUMINATION ITEMS

By Committee on Production and Application of Light

LIGHTS TOTALING TWENTY-FIVE MILLION CANDLE POWER BURN NIGHTLY ON BROADWAY SIGNS*

With 25,000,000 candle power of light flashed against the sky each night, New York's Great White Way is a challenge to the imagination and ingenuity of the advertising artist. One has but to saunter up Broadway at night time to see how well this challenge is being met with every conceivable device for attracting the attention of the vast crowds that throng the brightest spot in the world every evening. Of all these various devices, animated lights, with the extensive variety of motions they make possible, are seen to be in predominance. For the great power of moving lights lies in the fact that they help to tell a story vividly, and the advertiser who can get his story across to the public can be sure of its attention.

Like the proverbial moth, people head straight for a light, and moving light attracts more people than still illumination. The recognition of this truth, and the fact that bright lights have a stronger attraction for the eye than ordinary light, lies back of nearly all the newest developments for producing brilliant color and startling movements in electric signs. The instinct that compels us to look toward moving objects and to observe any object that is intensely bright is probably as old as the human race. Many explanations of its origin have been offered by scientists, but the important thing to recognize from the selling point of view is that such instincts are facts that must be reckoned with in the creation of all effective advertising.

The annual Electric Sign Show held by the New York Edison Company in the spring of this year afforded a splendid opportunity to compare the powers of attraction in still lights, colored and moving lights in electric signs. This show, the fourth of its kind and even more brilliant than the exhibitions of previous years, presented the latest ideas of sixty-five manufacturers from every branch of the electric sign industry. Everything new in electrical advertising, from simple glass box signs to the latest developments in flash devices and two-color animated billboards, were demonstrated.

A few days after the show was opened to the public, a revolving disk of colored light that threw off constantly changing prismatic colors was placed under the ordinary poster in the showroom window announcing the exhibition. Immediately the number of passersby who stopped before the window was more than trebled. There was hardly a person who was not drawn to the window almost automatically by the revolving disk of colored lights. As a consequence, the attendance at the Electric Sign Show grew from the normal number expected to a record attendance. It was the brilliant changing colors that caught the eyes of the passersby, even without their being aware of the fact, and fastened their attendance on the poster announcing the Electric Sign Show.

Observation of the crowds attending the exhibition revealed that of two similar signs, one illuminated and the other plain, the lighted bulletin attracted more than twice as many spectators as the unlighted one. The still sign, however, though illuminated, did not have as strong an attraction on the crowds as the sign across the aisle in which the effect of motion was produced by using a flasher. There was something in the power of the moving lights that almost automatically caught the eye of the spectators and thus drew their full attention to the advertisements.

Approximately 5000 electric signs were added to New York's skyline during the last year, an average of about fourteen a day. The blaze of animated light that illuminates the Great White Way today is quite a different story from the first electric sign of 30 years ago, which startled New Yorkers by its daring innovation and immediately made its mark as an effective form of advertising. The first electric sign, with its two hundred lamps, would almost be lost on Broadway now.

*—Signs of the Times—August, 1926.

JOURNAL OF THE American Institute of Electrical Engineers

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The Institute is not responsible for the statements and opinions given in the papers and discussions published herein. These are the views of individuals to whom they are credited and are not binding on the membership as a whole.

Pacific Coast Convention

SEPTEMBER 6-9

Preparations are complete for an excellent convention at Salt Lake City, September sixth to ninth inclusive. A most interesting collection of papers dealing with a wide range of subjects will be presented and a most enjoyable program of trips and entertainment has been arranged. The program is as follows:

Monday, September 6

9 A. M.

Registration at Convention Headquarters, Lobby Hotel Utah.

10 A. M.

Session of Counselors of Student Branches.

Meeting of Section Officers of Eighth and Ninth Geographical Districts.

12 M.

Organ Recital at Tabernacle.

2. P. M. Opening Session

Address of Welcome, by Governor Geo. H. Dern.

Response by President Cummings C. Chesney.

The Space Charge that Surrounds a Conductor in Corona, by H. J. Ryan and J. S. Carroll, Stanford University.

110-Kv. Transmission Line Construction of the Washington Water Power Co., by L. R. Gamble, Washington Water Power Co.

A New 220-Kv. Transmission Line, by C. B. Carlson and H. Michener, Southern California Edison Co.

Effect of Unbalanced Tension in a Long-Span Transmission Line, by E. S. Healy and A. J. Wright, Electric Bond and Share Co.

2 P.M.

Ladies drive about city and nearby canyons.

4:30 P.M.

Excursion to Saltair; bathing, dinner and dancing.

Tuesday, September 7

10 A. M. Technical Session

The Circle Diagram of a Transmission Network, by F. E. Terman, Stanford University.

Calibration of Lichtenberg Figures, by K. B. McEachron, General Electric Company.

Stability Characteristics of Alternators, by O. E. Shirley, General Electric Company.

Synchronizing Power in Synchronous Machines, by H. V. Putman, Westinghouse Electric & Manufacturing Company.

11 A.M.

Ladies drive to Country Club for Luncheon, followed by Golf on picturesque links of the Country Club.

2 P.M. Technical Session

Vacuum-Switching Experiments at California Institute of Technology, by R. W. Sorensen and H. E. Mendenhall, California Institute of Technology.

Economical Power Factor Correction, by S. H. Litchfield.

Electrical Practise in Lead-Silver Mines in Utah, by Leonard Wilson, Consulting Engineer.

Engineering Education: Its History and Prospects, by H. H. Henline, Stanford University.

8 P.M.

Informal Reception, Ballroom Hotel Utah. Music and Dancing.

Convention Headquarters, Salt Lake City

Wednesday, September 8

10 A.M. Technical Session

Protection of Oil Tanks Against Lightning,, by F. W. Peek, Jr., General Electric Co.

Fire Protection of A-C. Generators, by J. A. Johnson, Niagara Falls Power Co., and E. J. Burnham, General Electric Co.

Variable-Voltage Equipment for Electric Power Shovels, by R. W. McNeill, Westinghouse Electric & Manufacturing Co.

Temperature of a Contact and Related Current-Interruption Problems, by Joseph Slepian, Westinghouse Electric & Manufacturing Co.

11 A.M.

Ladies Excursion to Pinecrest Inn, at the head of Emigration Canyon, for lunch.

2 P.M.

Golf Tournament on Links of Country Club.

6:30 P.M.

Dinner, Hotel Utah Ballroom, followed by:
Presentation of Edison Medal
Response by Dr. Ryan

THURSDAY, SEPTEMBER 9

10 A.M. TECHNICAL SESSION

Transcontinental Telephony, by B. B. Jacobs and H. H. Nance, American Telephone and Telegraph Co.

LIBERTY PARK LAKE, SALT LAKE CITY

Controlling Insulation Difficulties in the Vicinity of Great Salt Lake, by B. F. Howard, Mountain States Telephone & Telegraph Co.

Carrier-Current Communication on Submarine Cables, by H. W. Hitchcock, Pacific Telephone and Telegraph Co.

BINGHAM CANYON EXCURSION

On Thursday, September 9, starting at 12 o'clock, there will be an excursion to Bingham Canyon and Magna, visiting the famous Mine and Mills of Utah Copper Company. Basket lunch will be served. This is a novel and instructive trip and will be enjoyed by the ladies. The excursion will be timed so that afternoon blasting can be witnessed from the opposite side of the canyon.

FRIDAY, SEPTEMBER 10

8 A.M.

Excursion via automobile to Utah Power & Light Company's new 30,000-kw. hydro generating station at Cutler on lower Bear River. The trip will be over paved roads the greater part of the way, passing through the cities of Ogden and Brigham. Excursion will return to Salt Lake City in time to catch evening trains the same day.

8 A.M.

Excursion over celebrated Bear Lake-Bear River Development of the Utah Power & Light Company by automobile. This is a 400-mile trip and will require two days' time. Excursion will return to Salt Lake City Saturday evening. Comfortable hotel arrangements have been made for the night stop. Part of the trip is through wonderful mountain and canyon scenery and will be enjoyed as much for the scenic beauty as for the technical and educational benefits.

New York to Have Regional Meeting in November

A two-day Regional Meeting is planned to be held in New York City, November 11 and 12. There will be four principal technical subjects discussed; namely, secondary distribution networks, illumination, communication, and railroad electrification. A number of excellent papers on these topics has been promised. In addition to the papers, other interesting features will be arranged, including inspection trips, entertainment, etc.

The committee in charge of the meeting is as follows: Messrs. H. A. Kidder, Chairman; H. V. Bozell, Secretary; O. B. Blackwell, W. A. Del Mar, G. L. Knight, E. B. Meyer and G. H. Stickney.

Chemists in Convention September 6th

Foreign delegates to the coming convention of the American Chemical Society are beginning to arrive in New York preparatory to meeting with probably the largest contingent that has ever visited America in attendance at the convention to be held in Philadelphia, September 6th. Among these early arrivals are Sir James Colquhoun Irvine, principal of the Scottish University of St. Andrews and head of its department of chemistry, Fellow of the Royal Society, Davy Medalist in 1925, and an eminent investigator of carbonhydrates; Leonor Michaelis,* Professor of biological chemistry, University of Berlin; Professor Ernst Cohen, Physical Chemistry Dept., University of Utrecht; Dr. Camille Matignon, editor-in-chief of Chimie et Industrie and head of research laboratory in College de France; and Gabriel Bertrand, Professor of biological Chemistry at the Sorbonne, chief of the service of biological chemistry of the Pasteur Institute and internationally known as a devotee of research.

Denmark will send J. N. Bronsted, Professor of Physical Chemistry at the Royal Polytechnic Institute, Copenhagen. He is also author of several textbooks on inorganic and physical chemistry and famous in research work.

Switzerland will send Peter Debye, Professor of Theoretical Physics at Technische Hochschule, Zurich. Prof. Debye is the author of numerous researches in physical chemistry, and is the leading exponent of the theory of the electrical structure of matter as applied to the problems of specific heats, dielectrics, and X-ray analysis.

Heading the delegation from Italy will be Prince P. Ginori Conti, who will address the American Chemical Society at Philadelphia, Monday evening, September 6, on "The Development of Chemical Industry in Italy."

Nearly four thousand scientists are expected to attend the Philadelphia sessions, and hundreds of papers and addresses will be delivered.

Annual Convention of Civil Engineers in October

The fifty-sixth annual convention of the American Society of Civil Engineers will be held October 4-9, 1926, at Philadelphia, Pa. The fact that at this same time, the Sesquicentennial Exposition celebrating the 150th anniversary of the signing of the Declaration of Independence, will be in progress also at Philadelphia, will enhance the attractions of the Convention and permit of a program planned for participation in the spirit of the Exposition as well as in the pleasures and scientific progress of the Convention itself. A large attendance is expected.

*Biochemistry in the Aichi Medical University, Nagoya, Japan, and author of numerous research papers.

A. I. E. E. Directors' Meeting

The first meeting of the Board of Directors of the American Institute of Electrical Engineers of the administrative year beginning August 1, 1926, was held at Institute headquarters, New York, on Tuesday, August 10.

There were present: President C. C. Chesney, Pittsfield, Mass.; Vice-Presidents A. G. Pierce, Cleveland; W. P. Dobson, Toronto; H. M. Hobart, Schenectady; B. G. Jamieson, Chicago; Managers W. K. Vanderpoel, H. P. Charlesworth, H. A. Kidder, New York; M. M. Fowler, Chicago; E. C. Stone, F. J. Chesterman, Pittsburgh; H. C. Don Carlos, Toronto; National Treasurer G. A. Hamilton, Elizabeth, N. J.; National Secretary F. L. Hutchinson, New York. Present by invitation: Past-President William McClellan and Dr. C. H. Sharp, President, U. S. National Committee of the International Electrotechnical Commission.

The minutes of the Directors' meeting of June 23, 1926, were approved as previously circulated.

A report was presented of a meeting of the Board of Examiners held July 26, 1926, and the actions taken at that meeting were approved. Upon the recommendation of the Board of Examiners the following actions were taken upon pending applications: 10 Students were ordered enrolled; 117 applicants were elected to the grade of Associate; 6 applicants were elected to the grade of Member; 2 applicants were transferred to the grade of Member; 1 applicant was transferred to the grade of Fellow.

Upon the recommendation of the Committee on Student Branches, authority was given for the organization of Student Branches of the Institute at Louisiana State University, Baton Rouge, La.; University of New Hampshire, Durham, N. H.; and Princeton University, Princeton, N. J.

Sections 46, 62, and 73 of the Institute by-laws were amended to read as follows:

"SEC. 46. The expenditures for transportation of Section delegates as referred to in the constitution shall be paid from the Institute treasury at the rate of ten cents (10c) per mile one way from the place of residence to the meeting place."

(This was done in order to place upon the uniform basis of ten cents per mile one way, the payment of traveling expenses of all delegates, officers, etc.)

"SEC. 62. The Board of Examiners shall consist of twelve Fellows of the Institute. The duties of this Board are defined in Section 44 of the constitution."

(To provide an increase in the number of members.)

"SEC. 73. The Committee on Award of Institute Prizes shall consist of the Chairman of the Meetings and Papers Committee acting as Chairman, and the chairmen of the Publication Committee, the Research Committee, and the chairmen of such other committees as the Board of Directors may designate."

(A change in personnel by the substitution of the chairman of the Research Committee for the chairman of the Committee on Power Transmission and Distribution.)

The Board approved plans for Regional Meetings, as follows: North Eastern District (No. 1), May 25-27, 1927, at a place to be decided by the District officers; Middle Eastern District (No. 2), April 14-16, 1927, at a place to be decided by the District officers; South West District (No. 7), February 14-15, 1927, Kansas City, Mo.

The appointment of committees, and of representatives of the Institute on various bodies, for the adminstrative year beginning August 1, 1926, was announced by President Chesney. (A list of these committees and representatives appears elsewhere in this issue.)

As required by the by-laws of the Edison Medal Committee, the Board confirmed the appointments by the President to the Edison Medal Committee, for the term of five years ending July 31, 1931, as follows: Messrs. John W. Howell, L. F. Morehouse, and David B. Rushmore; and the Board elected the following from its own membership to serve on this committee for the term of two years ending July 31, 1928: Messrs. B. G. Jamieson, H. A. Kidder, and G. L. Knight.

The following Local Honorary Secretaries were reappointed for the term of two years ending July 31, 1928: W. Eldson-Dew, for Transvaal; A. S. Garfield, for France; Carroll M. Mauseau, for Brazil; and F. W. Willis, for India.

A report was presented from a special committee appointed last year to consider the technical activites of the Institute, and upon the recommendation of that committee the Board adopted the following resolution:

"RESOLVED: That, effective with adoption of this resolution, the several Technical Committees shall assume a joint responsibility with the Standards Committee for the development and maintenance of such Institute Standards as come within their respective activities. Each technical committee shall report to the Committee on Standards such new standards or such changes in existing standards as are deemed desirable. Such recommendations shall be complete as to wording of any proposed standards. The Committee on Standards shall investigate and act on every such recommendation."

The Board approved a revision submitted by the Standards Committee, of Standards for Resistance Welding Apparatus (Section 39).

In acceptance of an invitation from the Committee of Award of the Kelvin Medal to nominate a candidate for consideration in the award of the 1926 Kelvin Medal, the Board voted that Sir Oliver Lodge be designated as the Institute's nominee.

The Secretary reported that the late Carl Hering had bequeathed to the A. I. E. E. and the Franklin Institute his books and professional apparatus, and that the matter had been referred to Director H. W. Craver of the Engineering Societies Library, who had arranged with the Franklin Institute for a division of this material.

Other matters of importance were discussed, reference to which may be found in this and future issues of the JOURNAL.

New Reports on A. I. E. E. Standards now Available

Three reports on proposed A. I. E. E. Standards are now available for purposes of criticism and suggestion before final adoption by the Institute. Copies may be obtained without charge by addressing H. E. Farrer, Secretary, A. I. E. E. Standards Committee, 33 West 39th Street, New York, N. Y. The reports referred to are as follows:

"Report on Lightning Arresters and Other Apparatus for Protection Against Abnormal Transient Voltages." This report was developed by a Working Committee of the Standards Committee under the chairmanship of F. L. Hunt, Chief Engineer, Turners Falls Power & Electric Company. This report covers service conditions, definitions, classification, rating, performance, earths and their resistances and dielectric tests for the following types of apparatus: Lightning arresters and diverters, lightning choke coils, high frequency absorbers, overhead grounded wires, earthing contacts and their resistances, length of connection between arresters and their earthing contacts or grounds.

"Report on Hard Drawn Aluminum Conductors." This report was developed by a Sectional Committee of the American Engineering Standards Committee under the sponsorship of the A. I. E. E. Mr. C. R. Harte, Construction Engineer, Connecticut Company, served as chairman.

"Report on Standards for Electrical Measuring Instruments." This report was prepared by a Working Committee of the Standards Committee under the chairmanship of G. A. Sawin, Westinghouse Electric & Manufacturing Company. The scope of the report is given as follows: Standards applying to the following kinds of indicating electrical instruments for direct current and alternating current; ammeters, voltmeters, wattmeters, reactive volt-ampere meters, frequency meters, power factor, reactive-factor and phase-angle meters, synchronoscopes.

Two New Swiss Standards Available

Standards for transformers not exceeding 500 volt-amperes and intended for interior installations. Special rules applying to transformers used in connection with bells, lock controls, and portable lamps, have been developed because of the conditions under which such apparatus is installed, often in damp inaccessible places and without intermediate circuit breakers.

Standards for insulated conductors for interior installations. The revision of the rules for erection and maintenance of interior installations has necessitated the working out of new standards for insulated conductors. To identify conductors that satisfy the new rules, a thread characterizing this quality has been introduced. Test methods are described in detail.

Both above standards may be obtained at office of General Secretary, Association Suisse des Electriciens, 301 Seefeldstrasse, Zurich, Switzerland.

American Engineering Standards Committee

A. E. S. YEAR BOOK FOR 1926

The 1926 edition of the American Engineering Standards Committee's Year Book is now ready for distribution and may be obtained by application to the secretary, P. G. Agnew, 29 West 39th Street, New York, N. Y. The Committee reports that the movement toward standardization of industrial products has shown marked progress during the past year, with over 200 definite standardization projects in process or completed, and with 365 national technical societies, government bureaus and trade associations collaborating through approximately 1600 representatives.

El Arte de los Metales

The Engineering Societies Library has to thank Mr. E. L. De Golyer, Vice-President of the Americau Institute of Mining and Metallurgical Engineers, for an unusually interesting addition to its collection of early engineering books. Mr. De Golyer's gift is a copy of the rare first edition of Albaro Alonzo Barba's "El Arte de los Metales," published at Madrid in 1640, the earliest work published on American metallurgy.

Barba was an Andalusian, born probably on November 5, 1561. He became a priest and prior to 1590 was sent to America. In 1615 we find him in Upper Peru (Bolivia), where he served various parishes for twenty-five years or more. He also became interested in mining, and in his book speaks of locating a vein of silver and erecting a mill. He claims to have discovered, in 1690, the method of pan amalgamation, and applied it successfully on a large scale.

His book is chiefly a detailed description of the metallurgical methods used in Peru, a topic on which his years of active work made him an authority. For many years it was in great demand, and French, German and Italian translations were published. In 1670 the Earl of Sandwich, then Ambassador Extraordinary of Great Britain, to Spain, published an English translation of the first two volumes of Barba's work, but his lack of technical knowledge made this of little value, and no adequate English translation appeared until 1923, when Messrs. Ross E. Douglass and E. P. Mathewson's translation was published in New York.

Copies of the first edition of the work are extremely scarce. Douglass and Mathewson state that they could locate but three copies, all of which were in the British Museum. Mr. De Golyer's copy is the fourth known here.

Among the various editions of Barba's book, another of special interest to Americans is one in German. This was published in 1763, at Ephrata, Pennsylvania. That the publication of a German translation, in Pennsylvania, over a century after the book was written, should appear a profitable publishing risk, is an evidence of the great esteem in which the work was held. The Engineering Societies Library is so fortunate as to possess a copy of this edition, in the original binding.

HARRISON W. CRAVER

Further Diesel Machinery Developments Sought

Plans to expedite experiments in dieselizing Shipping Board vessels were authorized by the Board on July 27th, according to official announcement made by T. V. O'Connor, Chairman, on the day following. Early arrangements will be made to work with William Francis Gibbs,—a nationally known marine engineer,—and others, for the purpose of making tests on vessels coming under control of the Board.

Coincident with this announcement, the American Marine Standards Committee held a meeting in New York City to discuss the care of diesel machinery. It is understood that the committee is working in cooperation with the Shipping Board, the Division of Simplified Practise of the Department of Commerce, and other interested government organizations.

Action Expected on Radio Measures

The radio bills known as the White Bill in the House and the Dill Bill in the Senate, both of which failed of enactment in the last session of Congress, are being sent to the members of the Conference Committee from both the House and Senate, and a meeting has been called for November in an effort to iron out the differences between these bills and to prepare a measure on which it is hoped both houses can agree early in the next session. In the meantime the Department of Commerce is continuing limited control of radio through the Bureau of Navigation. Technical problems concerning the development of the radio art from a scientific standpoint are centered in the radio laboratory of the Bureau of Standards.

Control of broadcasting through the licensing system has been relinquished but it is contemplated that the Department or the new commission will be able to bring these matters under control soon after the Law is enacted.

Civil Aviation Plans

Under the new civil aviation law, the Department of Commerce has taken jurisdiction over the lighting of postal airways, markings, and emergency landing facilities, and will take exclusive control of mapping of airways, charge of radio directional work, safety inspection of airplanes, licensing of pilots, and promote civil aviation generally.

This work will be under the immediate charge of William P. MacCracken, recently appointed Assistant Secretary of Commerce in Charge of Aviation under Secretary Hoover.

Divisions will be established in the Bureau of Lighthouses, Coast and Geodetic Survey and the Bureau of Standards to take up the highly specialized air development program. Under this arrangement, according to recent statements made by Secretary Hoover and Assistant Secretary MacCracken, early stimulation of civil aviation in the United States is confidently expected.

Study of Uses of Wood in Electrical Goods

A survey to determine the suitability of various grades of lumber for uses in the manufacture of electrical goods is to be made by L. N. Ericksen of the staff of the Forest Service's Forest Products Laboratory, as announced at the Department of Agriculture.

Deposits of Manganese Found

According to a statement just issued by the Geological Survey of the Department of the Interior, discovery of manganese ore deposits in the Olympic Mountain territory, State of Washington, lends color to the belief that other workable bodies of the ore will be found in that belt.

Manganese is used in the form of alloys in the production of steel and as a dioxide for the manufacture of dry-battery cells. The statement says that from preliminary figures it appears that in 1925 the new mines in Washington supplied approximately 11 per cent of the total high-grade metallurgical ore from domestic sources.

Developed Water Power in the United States

The Department of the Interior, through the Geological Survey, has just issued a report of the amount of developed water power in the United States as of January 1, 1926. This report shows that the capacity of water-wheels in plants of 100 h. p. or more on the first of this year was 11,176,596 h. p., an increase of 1,138,941 h. p., or about 11.5 per cent since March, 1925.

The total capacity in horse power of water-wheels in water-power plants in the United States for different years follows: 1908, 5,339,391 h. p.; 1921, 7,926,958 h. p.; 1924, 9.086,958 h. p.; 1925, 10,037,655 h. p.; 1926, 11,176,596 h. p. In the 17 years since 1908 the capacity of water-wheels in water-power plants has been more than doubled.

Engineering Societies Library

The library is a cooperative activity of the American Institute of Electrical Engineers, the American Society of Civil Engineers, the American Institute of Mining and Metallurgical Engineers and the American Society of Mechanical Engineers. It is administered for these Founder Societies by the United Engineering Society, as a public reference library of engineering and the allied sciences. It contains 150,000 volumes and pamphlets and receives currently most of the important periodicals in its field. It is housed in the Engineering Societies Building, 29 West Thirty-ninth St., New York.

In order to place the resources of the Library at the disposal of those unable to visit it in person, the Library is prepared to furnish lists of references to engineering subjects, copies or translations of articles, and similar assistance. Charges sufficient to cover the cost of this work are made.

The Library maintains a collection of modern technical books which may be rented by members residing in North America. A rental of five cents a day, plus transportation, is charged.

The Director of the Library will gladly give information concerning charges for the various kinds of service to those interested. In asking for information, letters should be made as definite as possible, so that the investigator may understand clearly what is desired.

The library is open from 9 a. m. to 10 p. m. on all week days except holidays throughout the year except during July and August when the hours are 9 a. m. to 5 p. m.

BOOK NOTICES (JULY 1-31, 1926)

Unless otherwise specified, books in this list have been presented by the publishers. The Society does not assume responsibility for any statement made; these are taken from the preface or the text of the book.

All books listed may be consulted in the Engineering Societies Library.

BELT CONVEYORS AND BELT ELEVATORS.

By Frederic V. Hetzel. 2nd edit., revised. N. Y., John Wiley & Sons, 1926. 333 pp., tables, diagrs., charts, 9 x 5 in., cloth. $5.00.

The work of an engineer with thirty years of experience in the design and operation of elevators and conveyors, this book is intended as a practical guide to the selection and operation of suitable belt elevating and conveying machinery.

This edition has been revised to include the improvements of recent years, particularly in the design of idlers and elevator buckets.

THE BONBRIGHT SURVEY OF ELECTRIC POWER AND LIGHT COMPANIES OF THE UNITED STATES: arranged according to Geographic Divisions. 3rd edit., revised to May 1, 1926. N. Y., McGraw-Hill Pub. Co., 173 pp., tables, maps, 11 x 8 in., paper. $5.00.

A series of maps and tables which show the electric companies that serve the incorporated places having 2500 or more people, together with the unincorporated towns of that size in Massachusetts, Rhode Island and New Hampshire. The statistics for each state include the population, number of families, number of telephones, number of automobiles, number of domestic lighting customers, value of crops, number of factories and wage earners, value of products, the primary horse power, and the population of each urban center. Those for the companies include their capital stock, funded debt, gross and net earnings, interest, and the communities that they serve.

BRASS INDUSTRY IN THE UNITED STATES.

By William G. Lathrop. Mt. Carmel, Conn., The Author. 1926. 174 pp., port., 7 x 5 in., cloth. Price not quoted.

An interesting account of the beginning of this important industry and of its later development. The author traces the early industrial development of Connecticut, shows why brass manufacture became of interest in that locality, and traces the gradual development of the industry and of the important firms engaged in it.

COLLOID CHEMISTRY: Theoretical and Applied. Vol. 1. Theory and Methods.

By Jerome Alexander, editor, N. Y., Chemical Catalog Company, 1926. 974 pp., illus., diagrs., 9 x 6 in., cloth. $14.50.

In 1922, the editor of this work solicited the assistance of other investigators of the chemistry of colloid in the preparation of a comprehensive book on that subject. The first fruits of this collaboration are the present book, on theory and methods, which is to be followed by others on the biological, medical and technological applications of colloid chemistry.

Volume One contains sixty papers discussing a wide variety of subjects and representing many views on theoretical questions. No attempt has been made to select contributors whose ideas and opinions agree; but to give instead the views of those who are actively engaged in this work, and to leave to the reader the task of judging.

THE ENGINEER AND THE PREVENTION OF MALARIA.

By Henry Home. Lond., Chapman & Hall, 1926. 176 pp., illus., diagrs., 8 x 5 in., cloth. 13s 6d.

The author of this book, an engineer with experience of the problem in a number of tropical countries, has endeavored to summarize the results of modern research and its practical application to mosquito destruction for the benefit of other engineers.

The first section discusses the identification of the malaria carrier and the initiation of anti-malarial schemes. Drainage and malarial conditions in lowland country, in towns and in hill country is then taken up, followed by chapters on the details of preventive works, on the value of antimalarial works and on biological means of attack. Appendixes by other authors treat of mosquito netting, applied entomology and house flies.

GEOMETRY OF ENGINEERING DRAWING: Descriptive Geometry by the Direct Method.

By George J. Hood. N. Y., McGraw-Hill Book. Co., 1926. 290 pp., diagrs., 9 x 5 in., cloth. $2.50.

Presents a new method of teaching descriptive geometry, used by the author for the last six years. This method avoids the use of planes of projection, quadrants, etc., and directs attention to the object itself, in agreement with engineering practise.

HYDRAULICS.

By Joseph N. Le Conte. N. Y., McGraw-Hill Book Co., 1926. 348 pp., diagrs., tables, 9 x 6 in., cloth. $3.00.

A textbook on the theoretical principles of hydraulics, which directs the attention of the student to first principles for the solution of most problems, instead of to empirical rules or tables. The aim is to teach the student to reason out the basic equations

and to master the fundamentals of the subject first by the use of pure mathematics and mechanics.

LIGHTHOUSE SERVICE.

By George Weiss. Balt., Johns Hopkins Press, 1926. (Institute for Government Research. Service monograph no. 40). 158 pp., 9 x 6 in., cloth. $1.00.

A study of the organization, functions, equipment and cost of the Lighthouse Service, with a compilation of the laws governing it and a bibliography of sources of information about it. The book is descriptive, not critical; its purpose being to give officials, members of Congress and the public, an accurate account of the service in detail.

MATERIALS OF CONSTRUCTION: their Manufacture and Properties.

By Adelbert P. Mills. 3rd edit., edited by Harrison W. Hayward. N. Y., John Wiley & Sons, 1926. 419 pp., diagrs., charts, 9 x 5 in., cloth. $4.00.

A general text-book, somewhat elementary in character, on the manufacture, properties and uses of the more common materials. The endeavor has been to give a modern treatment in a form concise enough for class use by students of civil engineering.

In this edition the text on the constitution of metals, alloy steels and alloys has been expanded, and the chapters on cement, concrete and timber have been revised.

METALLOGRAPHY AND HEAT TREATMENT OF IRON AND STEEL.

By Albert Sauveur. 3rd edition. N. Y., McGraw-Hill Book Co., 1926. 535 pp., illus., diagrs., table, 11 x 8 in., cloth. $8.00.

As might be expected after an interval of ten years, the third edition of this well-known textbook shows many changes from the second. About fifty pages of text have been added and the text has been rearranged. Much of the work has been rewritten, with the aim to make the book a satisfactory record of present views and of current practise.

ORGANIC SYNTHESES:

Edited by Henry Gilman and others. Vol. VI. N. Y., John Wiley & Sons, 1926. 120 pp., diagrs., 9 x 5 in., cloth. $1.50.

A collection of methods for the preparation of twenty-nine organic chemicals that are sometimes required by chemists and are not available commercially. These methods have been devised by various chemists and checked by others, to insure their practicability.

PRACTICAL COAL PRODUCTION: Mine Transportation and Market Preparation.

Compiled by Frank H. Kneeland. N. Y., McGraw-Hill Book Co., 1926. 354 pp., diagrs., 8 x 5 in., cloth. $3.00.

Covers the transfer of coal from the working face to the surface and its preparation for market. The compiler has selected the most approved methods from the literature on these topics and arranged the results of his investigations in a connected account.

LES PROGRES DE LA FONDERIE MOULAGE ET FUSION.

By C. Derulle. Paris, Masson & cie.; Gauthier Villars & cie, 1926. 256 pp., illus., diagrs., 8 x 5 in., paper. $0.88.

Not a treatise on foundry practise, but a review on broad lines of modern advances in founding and of the present state of the art. The author describes the methods of molding now in use, the furnaces, methods of casting and of finishing the castings. A chapter is devoted to foundry organization and cost-finding.

REFINING METALS ELECTRICALLY.

By Larry J. Barton. Cleveland, Penton Publ. Co., 1926. 414 pp., illus., tables, 9 x 6 in., cloth. $6.00.

A treatise on electric furnace practise in the foundry. The author discusses theoretical matters concisely, but devotes most attention to practical questions, such as the cost of electric melting, the choice of a furnace, preparing linings and making the various kinds of steel and iron. A selected bibliography is included.

WATER RATES AND STEAM CONSUMPTION OF MARINE MACHINERY.

By H. E. Brelsford and E. A. Stevens. N. Y., Simmons-Boardman Publ. Co., 1926. 169 pp., graphs, 8 x 5 in., cloth. $2.00.

The authors are respectively the Chief and the Senior Engineer of the Technical Section of the Emergency Fleet Corporation. While compiling standard performance curves for the ships of the Corporation they encountered great difficulty in establishing the fuel rates, which depend largely upon the water rates. A result of their experience is the present book, which presents a method for obtaining water rates and steam consumption with a reasonable degree of accuracy. The book discusses reciprocating engines, geared turbines and the auxiliary machines usual on ships. The necessary graphs and formulas are given and their use illustrated.

DIE WERKSTOFFE DES MASCHINENBAUES.

By A. Thum. Ber. & Lpz., Walter de Gruyter & Co., 1926. 2 v., illus., diagrs., 6 x 4 in., cloth. 1,50 r. m. each.

A textbook on the strength and properties of structural materials, written from the viewpoint of their use in mechanical engineering. The first volume discusses the qualities particularly needed in materials for machinery and the extent to which metals exhibit them. It also describes the methods of testing these qualities, and the varieties of iron and steel.

In Volume Two, the varieties of cast iron, structural steel, cast steel and non-ferrous alloys are described specifically, and the purposes for which each is suitable are mentioned. A chapter is devoted to such minor machine materials as wood, insulating materials, solders, etc.

PERSONAL MENTION

C. E. BURGOON has been appointed quarry manager of the Maule Ojus Rock Co., Ojus, Fla.

JACOB T. BARRON, formerly general superintendent of generation of the Public Service Electric and Gas Co., Newark, N. J., has been appointed general manager of the electric department of that company.

WILLIAM R. LYON, who has been in the System Operation Office of the Pennsylvania Power and Light Co. at Hazleton, Pa., recently resigned to go with the Products Protection Corporation of New Haven, Conn.

H. H. ROGGE has recently been selected by the Westinghouse Electric International Company to be special representative to the Philippine Islands. Mr. Rogge's territory will also include the Dutch East Indies, the Malay Peninsula, and Siam.

HERBERT S. SANDS, Vice-President of the A. I. E. E. for District No. 6 and manager of the industrial division of the Westinghouse Electric & Manufacturing Co. at Denver, has had the degree of Electrical Engineer conferred upon him by the University of Colorado.

HERMAN J. B. SCHARNBERG, formerly Chief Engineer of the Sugar Estates of Oriente, Inc., and Associated Companies, is now Chief Engineer of the Compania Azucarera Vertientes, Central Vertientes, Camaguey, Cuba. Mr. Scharnberg was elected a Life Fellow of the Royal Society of Arts last year.

IRVING E. BROOKE, formerly of Muir and Brooke, has opened an office at 1211 Security Bldg., 189 West Madison St., Chicago, for the practise of general engineering: design, supervision, investigation, and reports. He will specialize in power plants, heating, ventilating, plumbing and wiring systems, and mechanical equipment.

Obituary

Clifford Gray Linnell, born August 22, 1891, died July 2, 1926, after a short illness. Mr. Linnell joined the Institute in 1915. He was educated in the Brownville schools and later attended Clarkson College at Potsdam, N. Y. In 1913 he was given charge of the electrical and mechanical work for a large Massachusetts plant, but in 1915 joined the Aluminum Company of America, Massena, New York; he also spent some time with the Duquesne Light Company at Pittsburgh, Pa. In 1925 he resigned from the Duquesne Light Company to identify himself with the Westchester Lighting Company at Mount Vernon, New York, with which he was connected at the time of his death. He was chief of the Distribution Department, and valued for his diligent and capable service.

Henry Knox McIntyre, for seventeen years connected with the Electrical Department of the North Carolina State College,

and Professor of Electrical Application, died recently in the South. Professor McIntyre was a native of New York City,—born here April 25, 1877. He attended Lyon's Collegiate Institute and entered Columbia University, taking the regular four years' course in Electrical Engineering and obtaining his E. E. degree in 1899. He was first employed in the Testing Department of the Sprague Electric Co., of Bloomfield, N. J., but left them to enter the Engineering Department of the New York Telephone Company, where he did worthy work in their Research Department. One of the developments in which he assisted was the Gray Telautograph. Of recent years, he has been active in the development of electrometallurgical processes adaptable to the mineral resources of North Carolina. Professor McIntyre joined the Institute in 1902. He was a member, also, of the American Electrochemical Society.

Addresses Wanted

A list of members whose mail has been returned by the postal authorities is given below, together with the addresses as they now appear on the Institute records. Any member knowing the present address of any of these members is requested to communicate with the Secretary, at 33 West 39th St., New York, N. Y.

All members are urged to notify the Institute Headquarters promptly of any change in mailing or business address, thus relieving the member of needless annoyance, and also assuring the prompt delivery of Institute mail, the accuracy of our mailing records, and the elimination of unnecessary expense for postage and clerical work.

1.—A. F. Buckley, 211 Sherman Ave., New York, N. Y.
2.—S. G. Guth, 419 Hampton Ave., Wilkinsburg, Pa.
3.—A. R. Henry, 20 St. Nicholas St., Montreal, Que., Can.
4.—M. E. Johnson, 133 Ardsley Road, Schenectady, N. Y.
5.—A. G. Corbin, 753 Crescent Ave., Buffalo, N. Y.
6.—D. F. McConnell, 402 N. Highland Ave., Pittsburgh, Pa.
7.—J. P. Ortiz, N. Y. Edison Co., 23rd St. & 4th Ave., New York, N. Y.
8.—I. T. Roberts, 2355 Prarie Ave., Evanston, Ill.

Engineering Societies Employment Service

Under joint management of the national societies of Civil, Mining, Mechanical and Electrical Engineers cooperating with the Western Society of Engineers. The service is available only to their membership, and is maintained as a cooperative bureau by contributions from the societies and their individual members who are directly benefited.

Offices:—33 West 39th St., New York, N. Y.,—W. V. Brown, Manager.
53 West Jackson Blv'de., Room 1736, Chicago, Ill., A. K. Krauser, Manager.
57 Post St., San Francisco, Calif., N. D. Cook, Manager.

MEN AVAILABLE.—Brief announcements will be published without charge but will not be repeated except upon requests received after an interval of one month. Names and records will remain in the active files of the bureau for a period of three months and are renewable upon request. Notices for this Department should be addressed to ***EMPLOYMENT SERVICE, 33 West 39th Street, New York City,*** *and should be received prior to the 15th of the month.*

OPPORTUNITIES.—A Bulletin of engineering positions available is published weekly and is available to members of the Societies concerned at a subscription rate of $3 per quarter, or $10 per annum, payable in advance. Positions not filled promptly as a result of publication in the Bulletin may be announced herein, as formerly.

VOLUNTARY CONTRIBUTIONS.—Members obtaining positions through the medium of this service are invited to cooperate with the Societies in the financing of the work by nominal contributions made within thirty days after placement, on the basis of $10 for all positions paying a salary of $2000 or less per annum; $10 plus one per cent of all amounts in excess of $2000 per annum; temporary positions (of one month or less) three per cent of total salary received. The income contributed by the members, together with the finances appropriated by the four societies named above, will it is hoped, be sufficient not only to maintain, but to increase and extend the service.

REPLIES TO ANNOUNCEMENTS.—Replies to announcements published herein or in the Bulletin, should be addressed to the key number indicated in each case, with a two cent stamp attached for reforwarding, and forwarded to the Employment Service as above. Replies received by the bureau after the positions to which they refer have been filled will not be forwarded.

POSITIONS OPEN

DISTRIBUTION ENGINEERS, technically trained and preferably with one or more years' experience with overhead or underground distribution or both. The work covers the engineering design, layout and estimate of costs of distribution systems, for a group of large power companies. Opportunity. Apply by letter with full particulars regarding past experience, salary wanted, date when available, and references. Location, Middlewest. X-453C.

GRADUATE ELECTRICAL ENGINEER, experienced in small electric motors, to establish sales department with company manufacturing electric appliances. Opportunity. Apply by letter with full details of age, past employment and salary, and lowest salary to start. Location, Middlewest. X-117.

ASSISTANT ELECTRICAL ENGINEER, 35-40, to take charge of drawing room. Experience in the design, construction and operation of power plant, substation and transmission line equipment. Switches and switchboard design experience essential. Married man preferred. Salary $3600-$4000. Apply by letter only. Headquarters, Philadelphia. X-584C.S.

ASSISTANT INSTRUCTOR in applied electricity and electrical machinery for large technical school. Apply by letter giving education, experience, age, religion and salary desired. Opportunity. Location, East. X-606.

MEN AVAILABLE

ELECTRICAL GRADUATE of class 21/22, 25 years of age, single, four years of practical electrical experience in installation, maintenance and repair, including testing of electrical systems, machinery and their operation. C-1115.

GRADUATE ELECTRICAL ENGINEER, 26, single, three years' experience in construction and operation of mine and mill electrifications, desires position with concern manufacturing mine electrical appliances. C-1714.

ENGINEER, who has had fourteen years' experience in electrical engineering is available. A position of maintenance engineer or switchboard design, layout and power circuits' engineer, or engineer in charge of factory equipment is desired. The fourteen years' experience takes in one year test course, two years drafting on switchboard, floor layouts, etc., three years as an assistant foreman on factory maintenance of testing equipment and eight years as engineer in charge of all testing equipment. All of the above time was spent with the General Electric Company, Schenectady, New York. C-1649.

ASSISTANT TO VICE PRESIDENT of large, progressive electric utility company desires position of increased responsibility. Graduate electrical engineer with fifteen years' design, operating, executive training in public utility work, including three years with well known consulting firm. Present duties consist of acting as engineering consultant to vice president and handling capital improvement program, including engineering, job scheduling, budget control, miscellaneous management problems. B-754.

ELECTRICAL ENGINEER, 1926 graduate Colorado, 30, married, desires position with public utility or electrical contracting company. Nominal salary. Location preferred, West or Middlewest. C-1746.

PROFESSOR ELECTRICAL ENGINEERING, ten years of teaching experience covering all the regular and many specialized electrical courses. Contact with the industry has been broad and covers design, construction and application. Well acquainted with the educational needs of the engineering profession. Change desired because present position does not encourage research. B-7083.

MECHANICAL-ELECTRICAL GRADUATE ENGINEER, 25, single, extensive training with Westinghouse people and General Electric Com-

pany, Schenectady, New York, desires permanent position in locality of Boston with manufacturing concern or power plant, preferably in connection with generators and transmissions. Available on reasonable notice. C-1740.

MECHANICAL ELECTRICAL ENGINEER, married, eighteen years' experience covering General Electric test, substation and power station design and operation for steel and wire mills, electrical cable manufacturing and sales. Executive and industrial development ability. A-4652.

YOUNG UNIVERSITY PROFESSOR desires research laboratory position. Degrees E. E. and M. E. E. Nine months' experience in research laboratory of automotive equipment electrical company, four and one-half years' teaching experience in electrical engineering department. Has attended teachers' summer conference with Westinghouse. 31, married. C-1037.

INVESTIGATIONS, 40, single. Experienced engineer desires investigational work, preferably of electrical and mechanical laboratory research or development type. Ability tested in many ways. Reports on problems requiring originality and resourcefulness, and the supervision of others, most satisfactory. Location preferred, Middle-west. B-6273.

ELECTRICAL ENGINEER, technical graduate, married, twenty years' experience, ten with construction and public utility companies on design, construction and economic investigations of central, substation and factory installations, desires position with industrial plant, public utility or construction company. C-581.

ELECTRICAL ENGINEER, 28, single, with technical education. Five years' general electrical work, two years as assistant production manager in a manufacturing plant. Desires position in production or similar work where there is an opportunity to advance. Vicinity of New York preferred. Available immediately. B-8056.

PRODUCTION ENGINEER, A. I. E. E., 30, married, Engineering and Arts graduate; qualified by experience for Production Schedule, Budget or Valuation Engineering; 5 years Utility, four years' Industrial experience; prefer Managerial to strictly technical. Available Oct. 15, 1926. B-9676.

ELECTRICAL ENGINEER, . B. and M. S. degrees, 27, single. Experience—G. E. test course and three years with Transmission and Distribution Department of a large utility. Especially familiar with cables, transformers and distribution network problems. Connection with another utility or consulting firm on engineering and economic problems desired. Location preferred, south or east. C-1750.

UNIVERSITY GRADUATE, (1916), 35, single, Electrical and Mechanical Engineering, all-round experience, one year illumination tests, four years drafting and designing, especially automatic machinery; two years writing of technical reports and patent disclosures with patent drafting, mathematical computations. Besides English, speaks and writes three other languages. B-7214.

EXECUTIVE ELECTRICAL ENGINEER, 27, married, educated Canterbury College, now located with a prominent firm in New Zealand, handling all classes of Electrical plant, including heavy machinery and also household appliances, would like a change to U. S. A. Been accustomed to buying and price-fixing and also acting in a consulting capacity to clients requiring plant. Considerable experience in Public tendering. Available on short notice. Prepared to start at anything offering good chances of advancement. Would prefer West coast location. C-1763

FACTORY MANAGER OR ENGINEERING EXECUTIVE, 37, Technical Graduate 1911. Balanced experience in necessary branches leading to management includes shop apprenticeship, general engineering, production and management. Successful record shows cost reductions and abilities in analysis, invention, vision, and judgment. Fullest investigation of record and references invited. C-1776.

ELECTRICAL ENGINEER AND EXECUTIVE, 35, Married, 16 years' experience in operation, engineering and design of electrical apparatus. Has accomplished complicated design work. Has handled a large number of men. Desires position with manufacturing company as representative, sales engineer or responsible executive position. Has New York State Professional Engineer's license. C-1579.

COMMERCIAL ENGINEER, technical graduate, seven to eight years' experience in the public utility business on power and lighting sales, rates, engineering and operation. Desires connection with holding or management company of public utilities or with power company. Age 32, excellent health. Available on reasonable notice. B-9782.

ELECTRICAL & MECHANICAL ENGINEER, 24, single, graduate of Cornell, two years' experience in electrical plant, doing A. C. & D. C. assembly work, A. C. design, foundry work in connection with elevators, desires position, not particular about hours, work or location, would like position with plenty of work and good future, min. salary $160 a month. C-1769.

ELECTRICAL DESIGNER, 30, single, technical graduate, three years' practical experience in power station operation and factory, six years design electrical machinery and transformers, power and substations. Desires position with electrical manufacturing concern or power company offering opportunities for advancement. Available after two weeks' notice. Location, anywhere. C-10.

ELECTRICAL ENGINEER, 34, married, twelve years' experience in the design and operation of generating stations, substations, and transmission systems, eight years with large public utility, and four with industrial corporations. Recent extensive experience on automatic substations and supervisory control. Available in one month. Location, any, but North Central States preferred. C-635.

RECENT GRADUATE IN ELECTRICAL ENGINEERING, desires opportunity for foreign service. Testing and research experience. Position need not be strictly technical. Available within reasonable notice. C-348.

GENERAL EXECUTIVE, 43, married, mechanical and electrical engineer; five years manufacturing and engineering; ten years' commercial, five years' financial experience. Three years in charge of industrial re-organizations for large financial institution; keen analyst; good organizer. Available at once. A-4098.

ENGINEER, age 30, single, graduate E. E. with 7 years' experience in design and construction of Central stations, substations, and industrial Plants; also, distribution, overhead and underground. Available immediately. Location, immaterial. B-4662.

MEMBERSHIP — Applications, Elections, Transfers, Etc.

ASSOCIATES ELECTED AUGUST 10, 1926

AIYANGAR, SRINIVASA RAJAGOPALA, Managing Engineer, Sri Brahmavidyambal Electric Supply Corp., Ltd., Ramachandrapuram, Trichinopoly Dist., S. India.

ALLEN, ROBERT LIVINGSTON, Chief Engineer, Archbold-Brady Co., Greeneway Ave., Syracuse, N. Y.

ANDERSON, CLARE, Miscellaneous Engg. Dept., Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.

BAECKLER, WALTER, Electrical Engineer, National Carbon Co., Inc., West 117th St. & Madison Ave., Lakewood, Ohio.

BANKS, HAMPDEN OSBORNE, Electrical Inspector, Hartford Steam Boiler Inspection & Insurance Co., 80 Maiden Lane, New York, N. Y.

BARSE, JAMES HARPER, Elec. Draftsman, Engg. Dept., McKinney Steel Co., 3100 E. 45th St., Cleveland, Ohio.

BECKER, HUBERT, Jr., Interborough Rapid Transit Co., 600 W. 59th St., New York, N. Y.

BENNETT, R. S., Sales & Engineering, General Electric Co., 215 W. 3rd St., Cincinnati, Ohio.

BHUSARI, VASUDEO GANESH, Lecturer, V. J. Technical Institute, Matunga, Bombay, India.

*BLAKE, FRANK JEROME, Engineer, Outside Distribution Properties, Public Service Co. of Colorado, Gas & Elec. Bldg., Denver, Colo.

BOWEN, WILLIAM EARL, Asst. Valuation Engineer, Great Western Power Co., 375 Sutter St., San Francisco; res., Oakland, Calif.

BRAMBLETT, PAUL FRANCIS, Division Foreman, Northwestern Light & Power Co., Sibley, Iowa.

BRANSON, ALBERT KEMPER, Operator, Great Western Power Co. of California, 8425 Foothill Blvd., Oakland; for mail, Caribou, Plumas Co., Calif.

BROCKETT, NORWOOD W., Director of Public Relations, Puget Sound Power & Light Co., 860 Stuart Bldg., Seattle, Wash.

BURROW, PERCY, Supt. of Power Plant, Puget Sound Power & Light Co., Dryden, Wash.

BUTOW, F. W. C., Foreman, Electric Dept., Pacific Coast Steel Co., South San Francisco; res., San Bruno, Calif.

BUTTERWORTH, RUSSELL IRVIN, General Supt., Bristol Gas & Electric Co., Bristol, Tenn.

CAPRIN, VLADIMIR I., Electrification Dept., Illinois Central Railroad, Chicago, Ill.

CARRASCO-ZANINI, JUAN, Electrical Engineer, Mexican Light & Power Co., Donceles No. 80, Mexico, D. F., Mex.

CECCHETTI, FELIX, Testing Dept., General Electric Co., Erie Blvd., Schenectady, N. Y.

CHANG, ZUNG ZUE, Engineer, Engg. Dept., Westinghouse Elec. & Mfg. Co., Sharon, Pa.

CUNNINGHAM, KENNETH GEORGE, Trunk Engineer, Ohio Bell Telephone Co., 5300 Prospect Ave., Cleveland, Ohio.

CURTIS, HERBERT CRICHTON, Development Dept., Cutler-Hammer Mfg. Co., Milwaukee, Wis.

de LIMA, CLARENCE A., Radio Engineer, Westinghouse Electric International Co., Mexico D. F., Mex.

de MULINEN, EGBERT F. H., Electrical Engineer, American Brown Boveri Electric Corp., Camden; res., Haddon Heights, N. J.

DENNIS, EARLE M., Electrical Engineer, Bloedel Donovan Lumber Mills, Bellingham, Wash.

DICKINSON, ROBERT BIGLAND, Electrical Engineer, Engg. Dept., Duke Price Power Co., Ltd., Isle Maligne, Lake St. John, P. Q., Can.
DITESHEIM, GASTON J., Manager, Movado Co., 516 5th Ave., New York, N. Y.
DONALDSON, LESLIE JAMES, Asst. Engineer, Brown Boveri & Co., Ltd., Baden, Switzerland; for mail, Sydney, N. S. W., Aust.
DONOVAN, WALTER, Electrical Engineer, General Electric Co., Ltd., 6801 Glenwood Ave., Philadelphia, Pa.
DRAKE, RUSSEL ALONZO, Electrician's Mate, (3rd class), U. S. Navy, U. S. S. Arizona, San Francisco, Calif.
DUNKELBERG, PAUL R., Computor, Illinois Central Railroad Co., 109 E. Roosevelt Road, Chicago, Ill.
ENTEE, FRAMROZE DHUNJISHAW, Electrical Engineer, Century Mills, Parel, Bombay, India.
ESTRADA, JOSE FLORES, Asst. Electrical Engineer, Havana Central Railroad Co., Estacion Central, Havana, Cuba.
FOGG, LEIGH E., Cable Engineer, American Electrical Works, Phillipsdale, R. I.
GATTIKER, CARL H., Asst. Supt. of Construction, The New York Edison Co., 130 East 15th St., New York, N. Y.
GEARY, STEPHEN JOSEPH, Mains Supt., Municipal Electricity Dept., Christchurch, N. Z.
GILBERT, C. F., Chief Draftsman, Canadian Crocker-Wheeler Co., Ltd., St. Catharines, Ont., Can.
GILROY, JOHN R., Switchboard Operator, Commonwealth Edison Co., 25th & Quarry Sts., Chicago, Ill.
GRAY, WILBUR S., Draftsman, Stone & Webster, Inc., 147 Milk St., Boston, Mass.
GRONVOLD, INGVALD JULIAN, Electrician, Neil Electric Co., Isleton, Calif.
HAENTJENS, OTTO, President, Barrett, Haentjens & Co., Hazleton, Pa.
*HAMMOND, ROBERT JAMES, Supervising Engineer, The Pacific Tel. & Tel. Co., 1900 S. Grand, Los Angeles, Calif.
*HASTINGS, DONALD FRANCIS, Tester, Rossiter, Tyler & McDonell, 136 Liberty St., New York, N. Y.
HEINTZ, WILLIAM THEODOR, Sales Engineer, Automatic Electric Co., 427 Bourse Bldg., Philadelphia, Pa.
HEMSLEY, SYDNEY HENRICK, Power Transformer Designer, Messrs. Ferranti, Ltd., Hollinwood; for mail, Oldham, Lancashire, Eng.
HERNE, WALLACE WENDELL, Asst. Valuation Engineer, Great Western Power Co., San Francisco, Calif.
HILDEBRANDT, JOHN LAWRENCE, Research & Test Dept., Consolidated Gas, Electric Light & Power Co., Baltimore; res., Catonsville, Md.
HUDD, ALFRED ERNEST, Consulting Engineer, Automatic Electric Inc., 1033 W. Van Buren St., Chicago, Ill.
*HUMPHRIES, POWELL HORNER, Asst. in Elec. Engg. Dept., Harvard University, Pierce Hall, Cambridge; res., West Roxbury, Boston 32, Mass.
IRWIN, JAMES E., Elec. Constr. Foreman, Chile Exploration Co., Chuquicamata, Chile, So. Amer.
ISCHINGER, ALFRED ERNST, In charge of Engg. Dept., Joshua R. H. Potts, 929 Chestnut St., Philadelphia, Pa.
JAYNE, JOHN KENNON, Electric Representative, Autocar Co., 930 Bedford Ave., Brooklyn; res., New York, N. Y.
KEEFER, JOHN, Electrician, Pacific Coast Steel Co., South San Francisco, Calif.
KOHLHEPP, WILLIAM SAMUEL, Equipment Engineer, Cumberland Tel. & Tel. Co., Louisville, Ky.
LARKIN, JOHN J., Supt. of Signals, Brooklyn-Manhattan Transit Corp., 85 Clinton St., Brooklyn; res., Jamaica, N. Y.
LEON, CONSTANTINE, Jr., Electrical Engineer, Dept. of Electricity, Havana Central Railroad Co., Estacion Central, Havana, Cuba.
LESSING, OTTO, Cadet Engineer, Counties Gas & Electric Co., Penn & Markley Sts., Norristown, Pa.
LYDON, REGINALD JAMES BUNDY, Senior Instructor, Elec. Engg. Branch, Central Technical College, Brisbane, Queensland, Aust.
MacKAY, ALBERT TUTTLE, Inspector, Western Electric Co., 379 Summer St., Boston; res., Roslindale, Mass.
MacCORMICK, CHARLES M. C., Student Engineer, General Electric Co., Schenectady, N. Y.
*MADER, CLARENCE EDWARD, Student, Lewis Institute, 7704 Crandon Ave., Chicago, Ill.
MAHNKE, KURT, Draftsman, Pennsylvania Power & Light Co., 324 West St., Williamsport, Pa.
MAHONEY, JAMES FRANCIS, General Foreman, Brooklyn Edison Co., 14 Rockwell Place, Brooklyn, N. Y.
MARQUARDT, MAX, Electrician, 316 Rutherford Blvd., Passaic, N. J.
MARTINOV, VLADIMIR, Manager, Central & Substation Dept., State Electrotechnical Trust, 56 Prosp. of Oct. 25th, Leningrad, Russia.
MENDENHALL, WALKER HAMILTON, Asst. Engineer, Relay Dept., West Penn Power Co., 14 Wood St., Pittsburgh, Pa.
MERRITT, DAVID FRANKLIN, Electrical Mechanic, Famous Players Lasky Co., 1520 Vine St., Hollywood; res., Sherman, Calif.
METCALF, JAMES IRWIN, Reports Dept., Day & Zimmermann, Inc., 1600 Walnut St., Philadelphia, Pa., res., Bronxville, N. Y.
MILLER, NORBERT O. C., Owner, Schwall Electric Works, 429 E. Channel St., Stockton, Calif.
MOITINHO, RUBEN, Electrical Engineer-Government Inspector, Electrical Public Services; Secretaria Geral do Estado do Rio de Janeiro, Nictheroy, Brazil, So. America.
NAKAMURA, HIROSHI, Asst. Electrical Engineer, Toho Electric Power Co., Kaijo Bldg., Tokio, Japan; for mail, Wilkinsburg, Pa.
PALLONJI, D., Managing Engineer & Proprietor, Marine Electrical Engineering Works, Examiner Press Bldg., Dalal St., Fort Bombay, India.
PALM, I. ROBERT, Squad Man, Sargent & Lundy, 1407 Edison Bldg., Chicago, Ill.
PATRICK, RICHARD A., Electrical Mechanic, Truckee River Power Co., 21 Front St., Reno, Nev.
PINCKERT, WALTER F., Draftsman, Pacific Gas & Electric Co., San Francisco, Calif.
POUGY, ADHERBAL M., Chief Electrical Engineer, Cia Docas de Santos, Seccao Electrica, Santos, Brazil, So. Amer.
RAYMENT, EDWARD GEORGE, Foreman, Bethlehem Steel Co., Dock Central, La Plata, Arg. Rep., S. Amer.
REID, ALEXANDER, Production Engineer, Canadian Crocker-Wheeler Co., Ltd., St. Catharines, Ont., Can.
REID, MATTHEW, Resident Electrical Engineer, St. George County Council, Kogarah, Sydney, N. S. W., Aust.
ROGERS, FREDERICK HELME, Student Apprentice, Elec. Div., Consolidated Gas, Electric Light & Power Co., Baltimore, Md.
ROSADO, ANTONIO, Asst. Electrical Engineer, Havana Electric Railway, Light & Power Co., Monto No. 1, Habana, Cuba.
RUDORFF, DAGOBERT WILLIAM, Mechanical Asst. Engineer, Mexican Light & Power Co., Ltd., Necaxa, Puebla, Mex.
SANCHEZ, URBANO C., Supt., Distribution & Meter Dept., Compania de Electricidad de Merida, Yucatan, Mex.
SCHARF, PAUL BERNARD, Instructor, Mathematics & Science Dept., Goodyear Industrial University, Akron, Ohio.
SCHIFREEN, CLEMENT S., Electrical Designer, Philadelphia Electric Co., 1035 Chestnut St., Philadelphia, Pa.
SCHLEGEL, ROY DAVIS, Asst. Supt., Conduit Div., Potomac Electric Power Co., 213 14th St., N. W., Washington, D. C.
SHARROCK, LEWIS LEE, Electrical Draftsman, St. Lawrence County Utilities, Inc Potsdam, N. Y.
SKELTON, WILLIAM JOSEPH, Supervisor, Wisconsin Telephone Co., 1401 Clybourn St., Milwaukee, Wis.
SKINNER, ROBERT W., Construction Dept., Louisville Gas & Electric Co., Louisville, Ky.
STAGGS, NEWMAN K., Telephone Engineer & Contractor, The Telephone Engineering & Equipment Co., 216 Douglas Bldg., Seattle, Wash.
STEEL, EDWARD T., District Manager, Puget Sound Power & Light Co., Bremerton, Wash.
STEINMETZ, WILLIAM CLYDE, Supervisor, Telephone & Telegraph, The Alaska Railroad, Anchorage, Alaska.
SWANSON, EARL R., Division Engineer, Wisconsin Power & Light Co., Fond du Lac, Wis.
SYLVESTER, FRANK EDWIN, Supt., Substations, Great Western Power Co., 3729 Park Blvd., Oakland; res., Alameda, Calif.
TANDBERG, LEONARD G., Salesman, Wagner Electric Corp., 318 W. 15th St., Los Angeles, Calif.
TAYLOR, FRANK WARBURTON, Transformer Designer, Ferranti, Ltd., Hollinwood; res., Oldham, Lancashire, Eng.
TERHUNE, WALLACE IRVING, Engineering Assistant, Public Service Production Co., 80 Park Place, Newark, N. J.
THOMPSON, EUGENE PERCIVAL, Chief Electrical Engineer, St. George County Council, Kogarah, Sydney, Aust.
TILLQUIST, DAVID, Powerman, New York Telephone Co., 230 W. 36th St., New York, N. Y.
TORRES, SALVADOR EVARISTO, Foreman, Electrical Dept., Transcontinental Petroleum Co., La Barra Refinery, Tampico, Mexico.
VAN ETTEN, FRANK C., Manufacturers' Representative, 600 Joyce Realty Bldg., Columbus, Ohio; res., Chicago, Ill.
VAN WHY, FORBES WILLIAM, Radio Engineer-in-charge, Pasadena Star-News, 525 E. Colorado St., Pasadena, Calif.
VARLEY, HARRY, Managing Director, The Electric Motor & Stove Hiring Co., Ltd., Sweet St., Leeds, Yorkshire, Eng.
VONSOVICH, LEO J., Junior Engineer, Valuation Dept., Great Western Power Co. of California, Berkeley, Calif.
WALSH, FRANK, Supt. of Power, N. E. Dist., Puget Sound Power & Light Co., 3030 Colby St., Everett, Wash.
WARREN, PICKETT L., Salesman, Ohio Brass Co., 1714 Fisher Bldg., Chicago, Ill.
WATSON, STEWART CLARK, Switchboard Engineer, Switchboard Engg. Dept., Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.
WATTS, WILLIAM EWART GLADSTONE, Elec. Engineer in charge of Colliery Elec. Plant, Luscar Collieries, Luscar via Edmonton, Alta., Can.
WAY, ROBERT S., Power Engineer, Worcester Suburban Electric Co., Main St., Uxbridge, Mass.
WEAVER, R. A., Plant Engineer, Cincinnati & Suburban Bell Telephone Co., 225 E. 40th St., Cincinnati, Ohio.
WELLS, DONALD V., Division Manager, Northwestern Light & Power Co., Sibley, Iowa.

WHISENAND, OMER BURTON, Chief Electrician, Citizens Gas Co., 47 S. Pennsylvania St., Indianapolis, Ind.

WOLLEBAK, THOR, Designing Engineer, Delta Star Electric Co., 2433 Fulton St., Chicago, Ill.

Total 114

*Formerly Enrolled Students.

ASSOCIATES REELECTED AUGUST 10, 1926

BOYERE, EMERY E., Electrical Specialist, Small Motor Applications, 708 State St., Erie, Pa.

REHWALDT, ARTHUR W., Electrical Engineer, Sargent & Lundy, 72 W. Adams St., Chicago, Ill.

STOTLER, EDWIN JOHN, Elec. Engg., Sears, Roebuck & Co., 11 Astor St., Newark, N. J.; for mail, Chicago, Ill.

MEMBERS ELECTED AUGUST 10, 1926

BUTLER, M. BAYORD, Jr., Electrical Engineer, American Chain Co., Bridgeport; res. Waterbury, Conn.

JONES, REGINALD ELSDON, Asst. Engineer, Elec. Engg. Dept., Hydro-Electric Power Commission of Ontario, 190 University Ave., Toronto, Ont., Can.

SCHUMAN, JOSEPH HENRY, Engineer, Construction Bureau, The Edison Electric Illuminating Co. of Boston, 39 Boylston St., Boston, Mass.

THOMPSON, CHARLES SCOTT, Consulting Engineer, 1207 Medical Arts Bldg., Oklahoma City, Okla.

WESTBYE, JOHN, Designer, Gibbs & Hill, Pennsylvania Station, New York; res., Brooklyn, N. Y.

WHITE, WILLIAM COLLINS, Div. Transmission Engineer, Cumberland Tel. & Tel. Co., Louisville, Ky.

TRANSFERRED TO GRADE OF FELLOW AUGUST 10, 1926

McQUARRIE, JAMES L., Chief Engineer, International Standard Electric Corp., London, England.

TRANSFERRED TO GRADE OF MEMBER AUGUST 10, 1926

NORRIS, ERIC D. T., Technical Electrical Engineer, Ferranti Ltd., Hollinwood, Lancashire, England.

THOMAS, HERBERT P., Chief Engineer, Southland Electric Power Board, Invercargill, N. Z.

RECOMMENDED FOR TRANSFER

The Board of Examiners, at its meeting held July 26, 1926, recommended the following members for transfer to the grade of membership indicated. Any objection to these transfers should be filed at once with the National Secretary.

To Grade of Member

ANDREWS, HARDAGE L., Assistant Engineer, Railway Engineering Dept., General Electric Co., Schenectady, N. Y.

ANDREWS, JOSEPH F., American Tel. & Tel. Co., New York, N. Y.

AUTY, CLARENCE, Assistant Electrical Engineer, C. H. Tenney & Co., Boston, Mass.

BALE, LAWRENCE D., Supt. of Power, Cleveland Railway Co., Cleveland, Ohio.

BATES, LOUIS I., Engineer of Electric Distribution, Bronx Gas & Electric Co., New York, N. Y.

BENTON, JOHN R., Professor of Physics and Electrical Engineering, University of Florida, Gainesville, Fla.

BETTANNIER, EUGENE L., Electrical Engineer, Municipal Light & Power Department, Pasadena, Calif.

BOWMAN, HAROLD L., Service Engineer, Westinghouse Electric & Mfg. Co., New York, N. Y.

BROWN, HUGH A., Assistant Professor of Electrical Engineering, University of Illinois, Urbana, Ill.

CAVE, JOSEPH, Electrical Superintendent, Canadian General Electric Co., Toronto, Ont.

DREW, ERNEST C., Assistant Engineer, Bell Tel. Co. of Pennsylvania, Philadelphia, Pa.

DUBOSE, McNEELY, Electrical Superintendent, Aluminum Co. of Canada, Ltd., Arvida, Que.

FISHEL, ANTHONY D., Sales and Electrical Engineer, A. D. Fishel Co., Cleveland, Ohio.

FROM, OWEN C., Telephone Systems Engineer, Bell Telephone Laboratories, Inc., New York, N. Y.

GILLILAN, P. M., Railway Engineer, General Electric Co., Schenectady, N. Y.

GRAY, ROBERT, L., Electrical Engineer, Tararua Electric Power Board, Eketahuna, New Zealand.

HAMILTON, HAROLD C., Asst. Supt., Standardizing & Testing Dept., Edison Electric Illuminating Co. of Boston, Boston, Mass.

HART, R. PHILIP, Manager, Cazenovia Electric and Cazenovia Tel. Corp., Cazenovia, N. Y.

HENLINE, HENRY H., Associate Professor of Electrical Engineering, Stanford University, Stanford University, Calif.

HIGHT, WILLIAM R., Assistant Compass Engineer, Sperry Gyroscope Co., Brooklyn, N. Y.

JOHNSON, FRANCIS E., Professor of Electrical Engineering, University of Kansas, Lawrence, Kans.

KONGSTED, L. P., Research Engineer, American Bosch Magneto Corp., Springfield, Mass.

KURTZ, EDWIN, Professor and Head, Dept. of Electrical Engineering, Oklahoma A. & M. College, Stillwater, Okla.

LaROQUE, HAROLD B., Switchboard Engineering Dept., General Electric Co., Schenectady, N. Y.

McMILLAN, FRED O., Associate Professor of Electrical Engineering, Oregon State Agricultural College, Corvallis, Ore.

MICHENER, HAROLD, Asst. to Executive Engineer, Southern California Edison Co., Los Angeles, Calif.

MILLER, JOHN H., Chief Electrical Engineer, Jewell Electrical Instrument Co., Chicago, Ill.

MONG, CLIFFORD E., Engineer, Pacific Tel. & Tel. Co., Seattle, Wash.

MONROE, WENDELL P., Assistant Engineer, Illinois Central Railroad, Chicago, Ill.

MORROW, ALLEN, Department Head, Power Department, Standard Oil Co. of California, Richmond, Calif.

NETHERCUT, DONALD W., Distribution Supt., Ohio Public Service Co., Sandusky, Ohio.

NYMAN, ALEXANDER, Director, Radio Patents Corp., New York, N. Y.

O'NEAL, J. P., Westinghouse Electric & Mfg. Co., Sharon, Pa.

PACKARD, ANSEL A., Division Manager, Connecticut Power Co., Middletown, Conn.

PETERS, LEO J., Asst. Professor of Electrical Engineering, University of Wisconsin, Madison, Wis.

POTTS, LOUIS M., Electrical Engineer, Bell Telephone Laboratories, Inc., New York, N. Y.

READ, WALTER V., Telephone Engineer, American Tel & Tel. Co., New York, N. Y.

RODEY, BERNARD S., Jr., Engineer Accountant, United Electric Light & Power Co., New York, N. Y.

RYAN, FRANCIS M., Radio Engineer, Bell Tel. Laboratories, Inc., New York, N. Y.

SCHENCK, CHESTER, Materials Engineer, Elec. Engg. Dept., Commonwealth Power Corp., Jackson, Mich.

SHACKELFORD, BENJAMIN E., Chief Physicist, Westinghouse Lamp Co., Bloomfield, N. J.

THOMAS, RALPH L., Asst. to General Superintendent, Pennsylvania Water & Power Co., Baltimore, Md.

WORRALL, ROBERT H., Radio Engineer, U. S. Naval Research Laboratory, Bellevue, D. C.

APPLICATIONS FOR ELECTION

Applications have been received by the Secretary from the following candidates for election to membership in the Institute. Unless otherwise indicated, the applicant has applied for admission as an Associate. If the applicant has applied for direct admission to a higher grade than Associate, the grade follows immediately after the name. Any member objecting to the election of any of these candidates should so inform the Secretary before September 30, 1926.

Atkins, G. E., New England Tel & Tel Co., Boston, Mass.; for mail, New York, N. Y.

Atkinson, C. S., Shawinigan Water & Power Co., Montreal, P. Q., Can.

Bradt, A. W., (Member), Hamilton Hydro Electric System, Hamilton, Ont., Can.

Brandt, R., General Electric Co., Schenectady, N. Y.

Briggs, M. J., Stone & Webster, Tampa, Fla.

Brown, W. W., (Member), General Electric Co., Schenectady N. Y.

Campbell, I. S., Ohio Northern University, Ada, Ohio

Carter, T. E., Florida Power & Light Co., Miami, Fla.

Cosgrove, J. M., The Meaker Co., Chicago, Ill.

Cullwick, E. G., Canadian General Electric Co., Peterboro, Ont., Can.

Daniels, C. C., The Montana Power Co., Columbus, Mont.

de la Macorra, Jr., J., San Rafael Paper Co., Mexico City, Mex.

Duré, H. J. Edison Elec. Ill. Co. of Boston, Roxbury, Mass.

Finigan, W., Supt., Federal Trust & Clinton Bldg., Newark, N. J.

Fitzgerald, E. B., 28 Meridian St., Greenfield, Mass.

Foley, J. R., Appalachian Electric Power Co., Roanoke, Va.

Gatternigg, R., (Member), Pacific Portland Cement Cons. Co., Cement, Calif.

Gaylord, C. E., New York Telephone Co., Buffalo, N. Y.

Hall, H. M., American Copper Products Corp., New York, N. Y.
(Applicant for re-election.)

Huffman, G. A., New England Tel & Tel. Co., Boston, Mass.

Kempf, R. E., Pacific Oil & Lead Works, San Francisco, Calif.

Lucro, E. N., Public Service Production Co., Newark, N. J.

Lundgreen, S. O. G., General Electric Co., West Philadelphia, Pa.

Maiman, A., 2946 California St., San Francisco, Calif.

Max, C., Central Railroad Co. of New Jersey, Elizabethport, N. J.

Mayor, R., Jr., General Electric Co., Havana, Cuba

McLean, M. M. M., General Electric Co., West Lynn, Mass.

Miller, W. C., (Member), The Detroit Edison Co., Detroit, Mich.

Remaly, C. E., The R. Thomas & Sons Co., East Liverpool, Ohio

Remington, H. N., International Creosoting & Construction Co., Chicago, Ill.

Rienstra, A. R., Bell Telephone Laboratories, Inc., New York, N. Y.

Scanavino, S. A., Pacific Gas & Electric Co., San Francisco, Calif.

Schuler, Charles E., Asst. Chief Engineer, Elec. Dept., International Derrick & Equipment Co., Michigan & Buttles Aves., Columbus, Ohio

Stockwell, H. L., Tampa Electric Co., Tampa, Fla.

Storm, S. B., Marine Electric Co., Louisville, Ky.

Tefft, W. W., (Member), Commonwealth Power Corp., Jackson, Mich.
Wagner, H. H., Automatic Electric Co., Inc., Chicago, Ill.
Weissman, L. Hudson & Manhattan R. R. Co., New York, N. Y.
Wilson, H. R., Philadelphia Electric Co., Philadelphia, Pa.
Zuckerman, H., Wholesale Radio Equipment Co., New York, N. Y.
Total 40.

Foreign

Braudé, A. N., India Rubber Gutta-Percha & Telegraph Works Co., Ltd., London, Eng.
Campbell, F. W., Nottingham Corp., Nottingham, Eng.
Orbell, R. J., Thames Valley Power Board, Te Aroha, N. Z.
Peterson, A. W., Porto Rico Tel. Co., San Juan, Porto Rico
Poyitt, D. G., Municipal Council of Sydney, Sydney, N. S. W., Aust.
Stowers-Crowley, C. M. (Member), Opunake Elec. Pr. Board, Opunake, N. Z.
Sutherland, K., State Electricity Comm. of Victoria, Melbourne, Aust.
Total 7.

STUDENTS ENROLLED

Buckley, Chester F. Mass. Institute of Tech.
Feldman, Nikola, University of Latvia
Fluskey, Robert J., New York University
Gordon, Nathan B., Northeastern University
Lissner, Earle D., Massachusetts Inst. of Tech.
MacDonald, Hugh C., Northeastern University
Roake, Wilber C., Stevens Inst. of Tech.
Sanborn, John W., Mass. Inst. of Tech.
Veltre, Frank E. Jr., Georgia School of Tech.
Wheeler, Kimball L., Mass. Inst of Tech.
Total 10.

Officers A. I. E. E. 1926-1927

PRESIDENT

(Term expires July 31, 1927)
C. C. CHESNEY

JUNIOR PAST PRESIDENTS

(Term expires July 31, 1927) FARLEY OSGOOD
(Term expires July 31, 1928) M. I. PUPIN

VICE-PRESIDENTS

(Terms expire July 31, 1927)
P. M. DOWNING (District No. 8)
HERBERT S. SANDS (District No. 6)
W. E. MITCHELL (District No. 4)
ARTHUR G. PIERCE (District No. 2)
W. P. DOBSON (District No. 10)

(Terms expire July 31, 1928)
H. M. HOBART (District No. 1)
B. G. JAMIESON (District No. 5)
GEORGE L. KNIGHT (District No. 3)
H. H. SCHOOLFIELD (District No. 9)
A. E. BETTIS (District No. 7)

MANAGERS

(Terms expire July 31, 1927)
W. M. McCONAHEY
W. K. VANDERPOEL
H. P. CHARLESWORTH

(Terms expire July 31, 1928)
JOHN B. WHITEHEAD
J. M. BRYANT
E. B. MERRIAM

(Terms expire July 31, 1929)
M. M. FOWLER
H. A. KIDDER
E. C. STONE

(Terms expire July 31, 1930)
I. E. MOULTROP
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Sharon	H. L. Cole	L. E. Hill, Westinghouse Elec. & Mfg. Co., Sharon, Pa.

LIST OF SECTIONS—*Continued*

Name	Chairman	Secretary
Southern Virginia	W. S. Rodman	J. H. Berry, 1338 Rockbridge Ave., Norfolk, Va.
Spokane	Richard McKay	James B. Fisken, Washington Water Power Co., Lincoln & Trent, Spokane, Wash.
Springfield, Mass.	L. F. Curtis	J. Frank Murray, United Electric Light Co., 251 Wilbraham Ave., Springfield, Mass.
Syracuse	C. E. Dorr	F. E. Verdin, 615 City Bank Bldg., Syracuse, N. Y.
Toledo	A. H. Stebbins	Max Neuber, 1257 Fernwood Ave., Toledo, Ohio
Toronto	M. B. Hastings	F. F. Ambuhl, Toronto Hydro-Electric System, 226 Yonge St., Toronto, Ontario
Urbana	J. T. Tykociner	L. B. Archer, 308 Electrical Engineering Lab., University of Illinois, Urbana, Ill.
Utah	B. C. J. Wheatlake	D. L. Brundige, Utah Power & Light Co., Box 1790, Salt Lake City, Utah
Vancouver	R. L. Hall	C. W. Colvin, B. C. Electric Railway Co., 425 Carrall St., Vancouver, B. C.
Washington, D. C.	C. A. Robinson	D. S. Wegg, Elec. Equipment Div. Bureau of Foreign & Domestic Commerce, Washington, D. C.
Worcester	C. F. Hood	F. B. Crosby, Morgan Construction Co., 15 Belmont St., Worcester, Mass.
Total 51		

LIST OF BRANCHES

Name and Location	Chairman	Secretary	Counselor (Member of Faculty)
Alabama Polytechnic Institute, Auburn, Ala	J. D. Stewart	I. L. Knox	W. W. Hill
Alabama, University of, University, Ala	C.E. Rankin	Sewell St. John	
Arizona, University of, Tucson, Ariz	J. W. Cruse		Paul Cloke
Arkansas, University of, Fayetteville, Ark	Carroll Walsh	W. H. Mann	W. B. Stelzner
Armour Institute of Technology, Chicago, Ill	M. T. Goetz	C. W. Schramm	D. P. Moreton
Brooklyn Polytechnic Institute, Brooklyn, N. Y	F. Wanpel	Joseph Heller	Robin Beach
Bucknell University, Lewisburg, Pa	A. Fogelsanger	J. D. Johnson	W. K. Rhodes
California Institute of Technology, Pasadena, Calif	Thomas Gottier	Alan Capon	R. W. Sorensen
California, University of, Berkeley, Calif	C. F. Dalziel	R. S. Briggs	T. C. McFarland
Carnegie Institute of Technology, Pittsburgh, Pa	J. R. Power	R. O. Perrine	B. C. Dennison
Case School of Applied Science, Cleveland, O	C. A. Baldwin	A. B. Anderson	H. B. Dates
Catholic University of America, Washington, D. C	B. J. Kroeger	J. E. O'Brien	T. J. MacKavanaugh
Cincinnati, University of, Cincinnati, O	F. Sanford	W. C. Osterbrock	W. C. Osterbrock
Clarkson College of Technology, Potsdam, N. Y	W. R. MacGregor	L. G. Carney	A. R. Powers
Clemson Agricultural College, Clemson College, S. C	B. V. Martin	W. H. Sudlow	S. R. Rhodes
Colorado State Agricultural College, Ft. Collins, Colo	C. O. Nelson	D. W. Asay	
Colorado, Univerxity of, Boulder, Colo	A. D. Thomas	J. A. Setter	W. C. DuVall
Cooper Union, New York, N. Y	F. H. Miller	H. T. Wilhelm	Norman L. Towle
Denver, University of, Denver, Colo	Harold Henson	Allea Ohlson	R. E. Nyswander
Drexel Institute, Philadelphia, Pa	H. D. Baker	R. S. Eininger, Jr.	E. O. Lange
Florida, University of, Gainesville, Fla	O. B. Turbyfill	R. Theo. Lundy	J. M. Weil
Georgia School of Technology, Atlanta, Ga	W. M. McGraw	F. L. Kaestle	E. S. Hannaford
Idaho, University of, Moscow, Idaho	J. W. Gartin	S. Blore	J. H. Johnson
Iowa State College, Ames, Iowa	P. E. Benner	H. J. Biddulph	F. A. Fish
Iowa, University of, Iowa City, Iowa	L. Dimond	A. C. Boeke	A. H. Ford
Kansas State College, Manhattan, Kans	A. M. Young	John Yost	C. E. Reid
Kansas, University of, Lawrence, Kans	W. L. Immer	H. R. Hilkey	G. C. Shaad
Kentucky, University of, Lexington, Ky	J. A. Weingartner	C. E. Albert	
Lafayette College, Easton, Pa	A. H. Gabert	F. G. Keim	Morland Kin g
Lehigh University, S. Bethlehem, Pa	F. G. Kear	J. H. Shuhart	J. L. Beaver
Lewis Institute, Chicago, Ill	O. D. Westerberg	R. G. Raymond	F. A. Rogers
Maine, University of, Orono, Me	S. B. Coleman	H. S. McPhee	W. E. Barrows, Jr.
Marquette University, Milwaukee, Wis	C. H. Legler	M. J. Smith	J. F. H. Douglas
Massachusetts Institute of Technology, Cambridge, Mass	Stuart John	H. W. Geyer	W. H. Timbie
Michigan State College, East Lansing	Mr. Way	Mr. Phelps	L. S. Foltz
Michigan, University of, Ann Arbor, Mich	M. H. Nelson	H. R. Stevenson	B. F. Bailey
Milwaukee, Engineering School of, Milwaukee, Wis	S. A. Moore	B. J. Chromy	B. A. Bovee
Minnesota, University of, Minneapolis, Minn	C. H. Burmeister	J. H. DuBois	H. Kuhlmann
Missouri, University of, Columbia, Mo	M. P. Weinbach	L. Spraragen	M. P. Weinbach
Missouri School of Mines and Metallurgy, Rolla, Mo	W. J. Maulder	R. P. Baumgartner	I. H. Lovett
Montana State College, Bozeman, Mont	W. E. Pakala	J. A. Thaler	J. A. Thaler
Nebraska, University of, Lincoln, Neb	R. Worrest	C. J. Madsen	F. W. Norris
Nevada, University of, Reno, Nev	George Fairbrother	Cornelius Fort	S. G. Palmer
New York, College of the City of, New York, N. Y	Harold Wolf	J. Leipziger	Harry Baum
New York University, New York, N. Y	H. U. Hefty	Henry Och	J. Loring Arnold
North Carolina State College, Raleigh, N. C	F. P. Dickens	H. Baum	G. C. Cox
North Carolina, University of, Chapel Hill	H. L. Coe	C. M. Lear	P. H. Daggett
North Dakota, University of, University	V. L. Cox	O. B. Medalen	D. R. Jenkins
Northeastern University, Boston, Mass	W. P. Raffone	John L. Clark	W. L. Smith
Notre Dame, University of, Notre Dame, Ind	C. A. Rogge	J. T. Burton	J. A. Caparo
Ohio Northern University, Ada, Ohio	M. Heft	P. W. Wadsworth	J. W. Gray
Ohio State University, Columbus, O	Lee P. Doyle	J. S. Hoddy	F. C. Caldwell
Ohio University, Athens, Ohio	N. R. Smith	J. E. Quick	A. A. Atkinson
Oklahoma A. & M. College, Stillwater, Okla	W. J. Beckett	Lee Rogers	Edwin Kurtz
Oklahoma, University of, Norman, Okla	G. B. Brady	J. C. Glaze	F. G. Tappan
Oregon Agricultural College, Corvallis, Ore	F. D. Crowther	E. F. Reddy	F. O. McMillan
Pennsylvania State College, State College, Pa	F. F. Wilkins	C. C. Huggler	L. A. Doggett
Pennsylvania, University of, Philadelphia	F. H. Riordan, Jr.	W. H. Hamilton	C. D. Fawcett
Pittsburgh, University of, Pittsburgh, Pa	S. A. Swetonic	L. M. Brush	H. E. Dyche
Purdue University, Lafayette, Ind	A. Howard	T. B. Holliday	A. N. Topping
Rensselaer Polytechnic Institute, Troy, N. Y	F. M. Sebast	K. C. Wilsey	F. M. Sebast
Rhode Island State College, Kingston, R. I	G. A. Eddy	C. Easterbrooks	Wm. Anderson
Rose Polytechnic Institute, Terre Haute, Ind	J. H. Utt	E. Letsinger	C. C. Knipmeyer
Rutgers University, New Brunswick, N. J	E. C. Siddons	W. H. Bohlke	F. F. Thompson
South Dakota State School of Mines, Rapid City, S. D	C. Allen	Harold Eade	J. O. Kammerman
South Dakota, University of, Vermillion, S. D	L. J. Stverak	R. T. Brackett	B. B. Brackett
Southern California, University of, Los Angeles, Calif	J. H. Shideler	E. E. Smith	C. E. Guse
Stanford University, Stanford University, Calif	A. V. Pering	J. G. Sharp	H. H. Henline
Stevens Institute of Technology, Hoboken, N. J	D. B. Wesstrom	Gene Witham	Frank C. Stockwell
Swarthmore College, Swarthmore, Pa	J. S. Donal, Jr.	R. W. Lafore	Lewis Fussell
Syracuse University, Syracuse, N. Y	K. N. Cook	R. H. Watkins	C. W. Henderson
Tennessee, University of, Knoxville, Tenn	F. N. Green	B. M. Gallaher	Charles A. Perkins
Texas A. & M. College, College Station, Texas	L. H. Cardwell	C. A. Altenbern	F. C. Bolton
Texas, University of, Austin, Tex	F. W. Langner	H. W. Zuch	J. A. Correll
Utah, University of, Salt Lake City, Utah	F. C. Bates	C. E. Hoffman	J. F. Merrill
Virginia Military Institute, Lexington, Va	R. P. Williamson	M. L. Waring	S. W. Anderson
Virginia Polytechnic Institute, Blacksburg, Va	M. R. Staley	R. M. Hutcheson	Claudius Lee
Virginia, University of, University, Va	R. C. Small	G. L. Lefevre	W. S. Rodman
Washington, State College of, Pullman, Wash	S. H. White	H. R. Meahl	H. V. Carpenter
Washington University, St. Louis, Mo	E. B. Kempster, Jr.	George Simpson	H. G. Hake
Washington, University of, Seattle, Wash	C. M. Murray, Jr.	Roy H. Crosby	George S. Smith
Washington and Lee University, Lexington, Va	D. S. McCorkle	C. M. Wood	R. W. Dickey
West Virginia University, Morgantown, W. Va	R. W. Beardslee	W. F. Davis	A. H. Forman
Wisconsin, University of, Madison, Wis	Benj. Teare	N. B. Thayer	C. M. Jansky
Worcester Polytechnic Institute, Worcester, Mass	D. A. Calder	C. H. Kauke	H. A. Maxfield
Wyoming, University of, Laramie, Wyo	John Hicks	J. O. Yates	G. H. Sechrist
Yale University, New Haven, Conn	S. A. Tucker	G. C. Bailey	Charles F. Scott
Total 87			

DIGEST OF CURRENT INDUSTRIAL NEWS

NEW CATALOGUES AND OTHER PUBLICATIONS

Mailed to interested readers by issuing companies

Transformers.—Bulletin GEA-424, 72 pp. Describes G-E distribution and small power transformers. General Electric Company, Schenectady, N. Y.

Radio Frequency Ammeters.—Bulletin 810, 4 pp. Describes the Roller-Smith thermal ammeters and milli-ammeters for measuring radio frequency currents. Roller-Smith Company, 12 Park Place, New York.

Automatic Stations.—Bulletin GEA-90A, 48 pp. Describes G-E automatic stations. Numerous installations in various industries are pictured in the book. General Electric Co., Schenectady, N. Y.

Jagabi Rheostats.—Catalog 1140, 20 pp. Describes a line of adjustable resistances suitable for practically every need in electrical, physical, chemical, research and educational laboratories. A number of improvements have recently been made in these devices. James G. Biddle, 1211 Arch Street, Philadelphia, Pa.

Watthour Meters.—Bulletin C1753, 16 pp., "Registers of Revenue," is a Westinghouse publication dealing with the advantages of the watthour meter. The permanent accuracy of the meter, low costs of adjustments, tests and handling, ease in reading and saving of storage space are some of the points covered. Westinghouse Electric & Mfg. Company, East Pittsburgh, Pa.

NOTES OF THE INDUSTRY

Edgar S. Bloom elected President of the Western Electric Company.—Election of Edgar S. Bloom, a vice-president of the American Telephone and Telegraph Company, to the presidency of the Western Electric Company, has been announced. He succeeds Charles G. DuBois, who has been president for the past seven years, and who continues with the company as Chairman of the Board of Directors.

Harry S. Schott appointed General Sales Manager of National Carbon Company, Inc.—The appointment on August 1 of Harry S. Schott as general sales manager of the National Carbon Company, Inc. has been announced. He has been associated with the company since 1913, and has been identified with the manufacturing and jobbing end of the electrical industry for almost twenty-five years.

The Kuhlman Electric Company, Bay City, Michigan, manufacturers of power, distribution and street lighting transformers, announces the appointment of H. F. Darby, Jr., 1700 Walnut Street, Philadelphia, Pa., as direct factory representative in the Philadelphia district. For more than twenty years Mr. Darby was with the Cutter Electrical & Manufacturing Company and during the last six years he was sales manager of that organization.

The Jas. R. Kearney Corporation is Organized.—James R. Kearney, for the past fifteen years associated with the W. N. Matthews Corporation, is president of the new Jas. R. Kearney Corporation, manufacturers of utility equipment, located at 4224-32 Clayton Avenue, St. Louis, Mo. Mr. Kearney has had wide experience in specialty equipment manufacturing, plant engineering and pole line and underground construction. A number of well known specialties are manufactured under his patents. A group of engineers and well known figures in the electrical industry are associated with Mr. Kearney in his new enterprise.

Great Increase in Exports of U. S. Products.—The Bureau of Foreign and Domestic Commerce reports that exports of finished manufactures show an increase during the fiscal year just ended, of 16 per cent over the previous year. They were 60 per cent greater than in 1921-1922 and nearly three times as great in value as in the five year period before the war. Even after allowing for higher prices, they were more than double the pre-war average. Dr. Julius Klein, Director of the Bureau, states that this large growth reflects the ever rising efficiency of American industry and the energy and intelligence of American salesmanship in foreign markets.

The export of electrical machinery and apparatus amounted to over $80,000,000 in the fiscal year 1925-1926, as compared to $67,000,000 in 1924-1925 and $57,000,000 for the year 1921-1922. The total value of the exports of semi-manufactures and finished manufactures amounted to $2,573,000,000 for the fiscal year 1925-1926, an increase of 50 per cent in five years.

Equipment for Conowingo.—Three vertical-shaft hydraulic turbines, each of 54,000 horse power, will be constructed by the William Cramp & Sons Ship & Engine Building Company, of Philadelphia, in carrying out the great power development of the Philadelphia Electric Company at Conowingo, on the Susquehanna River. Though they are exceeded by a few installations in power capacity, on account of the lower head requirements the physical dimensions of the new units will exceed those of any hydraulic turbine yet constructed. The head at Conowingo will be 89 feet and the turbines will operate at a speed of 81.8 revolutions per minute.

The General Electric Company will supply thirteen transformers for the Conowingo project. These are to be used in transmitting 350,000 horse power of electrical energy over seventy miles of transmission lines to Philadelphia. Each of the transformers, all of the water-cooled type, has a rated capacity of 26,667 kilovolt-amperes. The voltage will be stepped up from 13,800, at which the current will be generated, to 220,000, at which it will be transmitted. The transformers have an efficiency of better than 99 per cent.

Two Million Dollar Turbine Generator Contracts for Westinghouse.—Substantial increases in electric power production, both central station output as well as industrial power, are reflected in several contracts for power generating equipment just received by the Westinghouse Electric and Manufacturing Company. The contracts aggregate a total of 120,000 electric horse power, of which approximately 90,000 will be for additional power company current, and when completed will represent an outlay of approximately $2,000,000.

The biggest contract was placed by the Duquesne Light Company for one turbine generator of 60,000 horse power, one 62,500 square-foot steam condenser with auxiliaries and three transformers, each rated at 31,400 kv-a. The equipment is to be installed at the Colfax Station at Cheswick. This station at the present time has four generator units of approximately 250,000 horse power.

A contract placed by the Binghamton Light Heat & Power Company, Binghamton, New York, calls for delivery of one 45,000 horse power turbine generator as well as three transformers rated at 11,765 kv-a. each. The equipment is to be installed at the company's power station at Binghamton.

The third contract was received from the Solvay Process Company of Syracuse, New York, and includes two high pressure turbine generators of unusual design and of a total of approximately 15,000 horse power. While ordinarily big steam turbines operate at a steam pressure of from 200 to 400 pounds, these turbines will have a gage throttle pressure of seven hundred and twenty-five pounds. The installation is intended primarily to obtain steam economies and utilize by-product power.

All the steam power equipment will be built at the South Philadelphia Works, while the electrical equipment will be supplied by the East Pittsburgh shops.